

Innovations in Synthetic Aperture Radar for Earth Applications – Past, Present, and Future

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Jet Propulsion Laboratory, California Institute of Technology



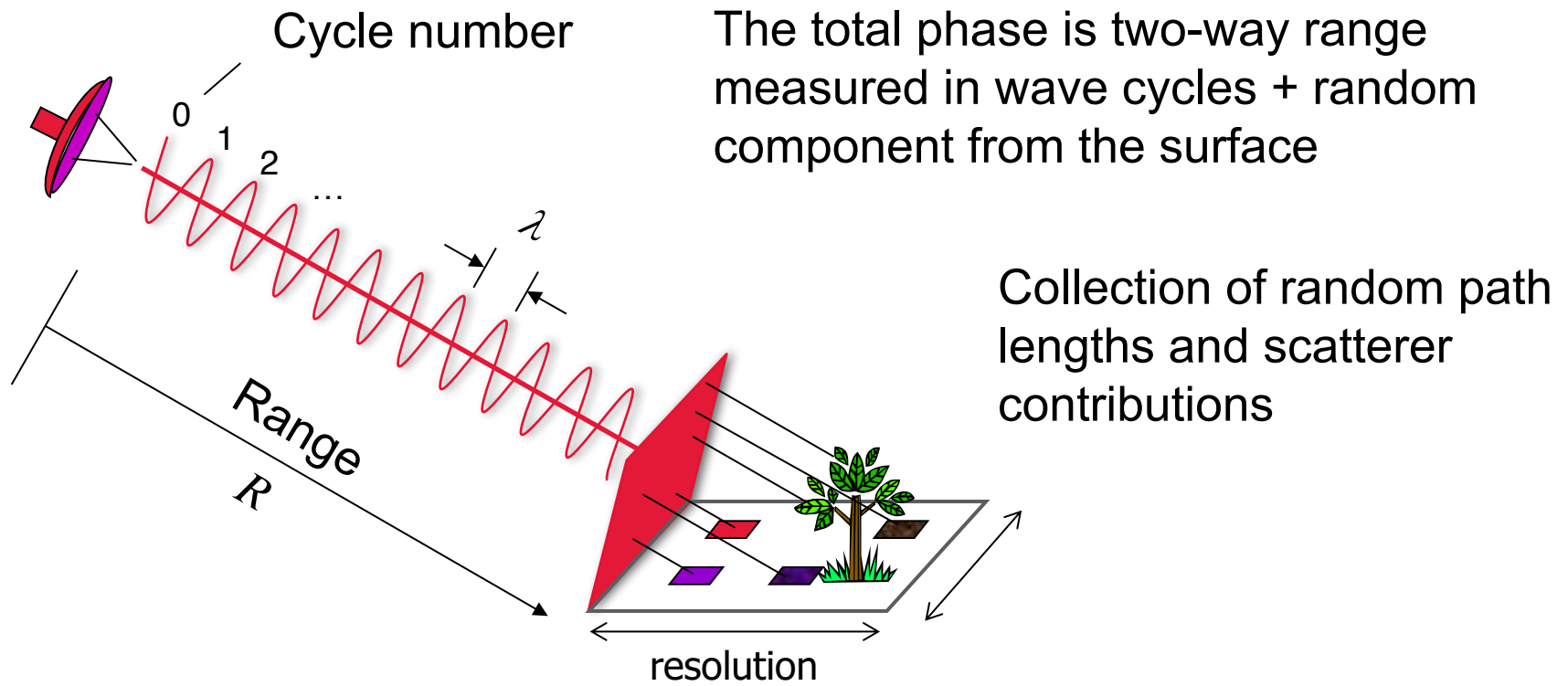
Jet Propulsion Laboratory
California Institute of Technology

Outline of talk

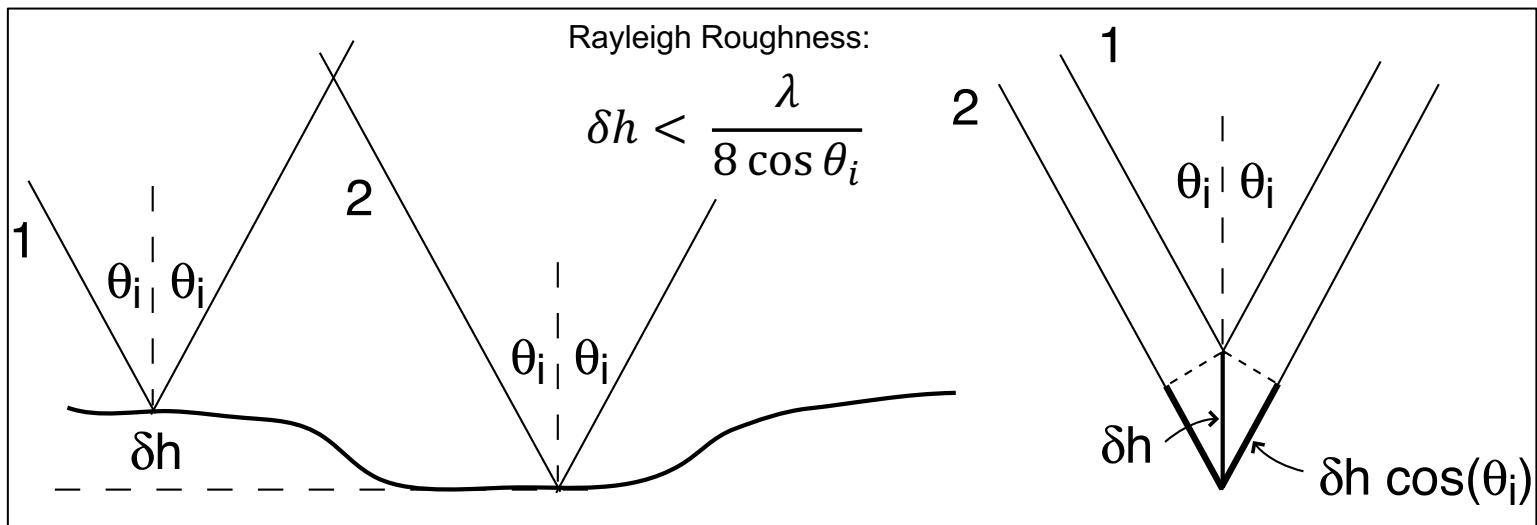
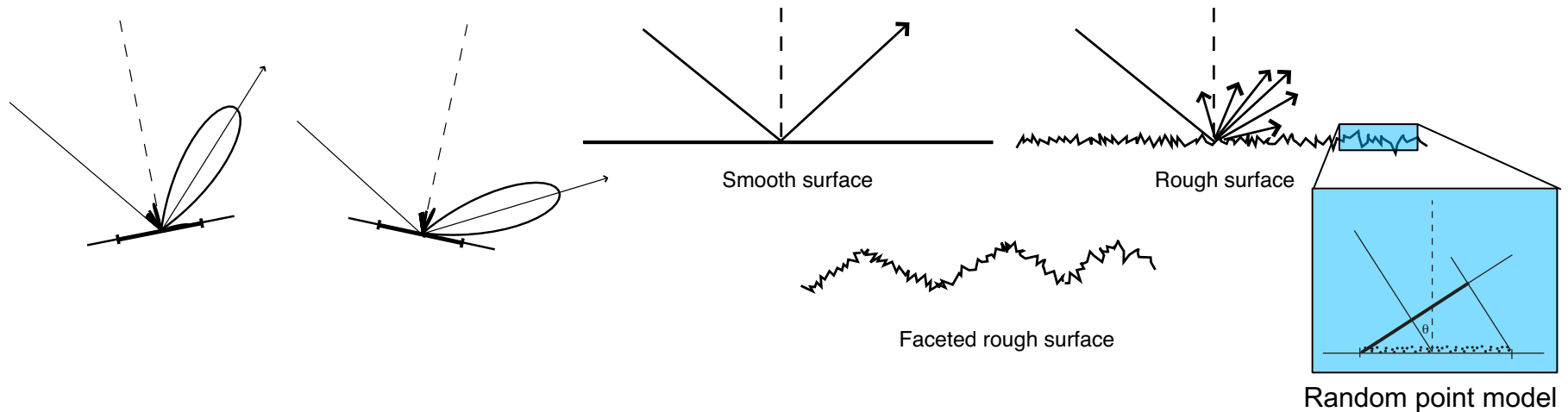
- Why Synthetic Aperture Radar?
- Historical Perspective on SAR Applications
- The present day Renaissance in SAR
- Prospects for the future

Radar Phenomenology

The radar view of a surface depends on the design features of the radar – its wavelength, polarization, resolution, and phase characteristics



Surface and Volume Scattering for Radar

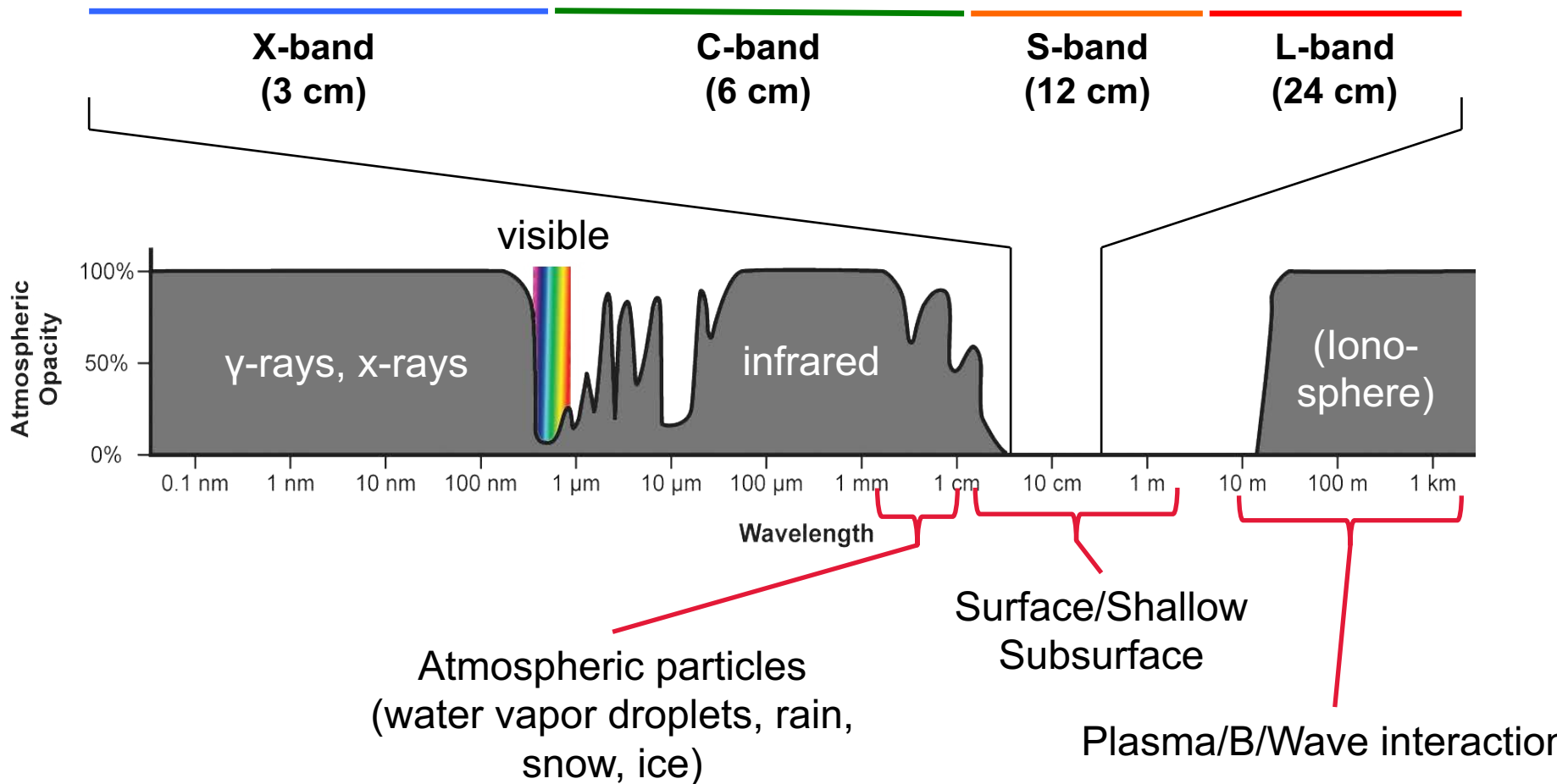


The Tyranny of Optical Remote Sensing



Atmospheric Windows and Radar

Common Land/sea imaging bands



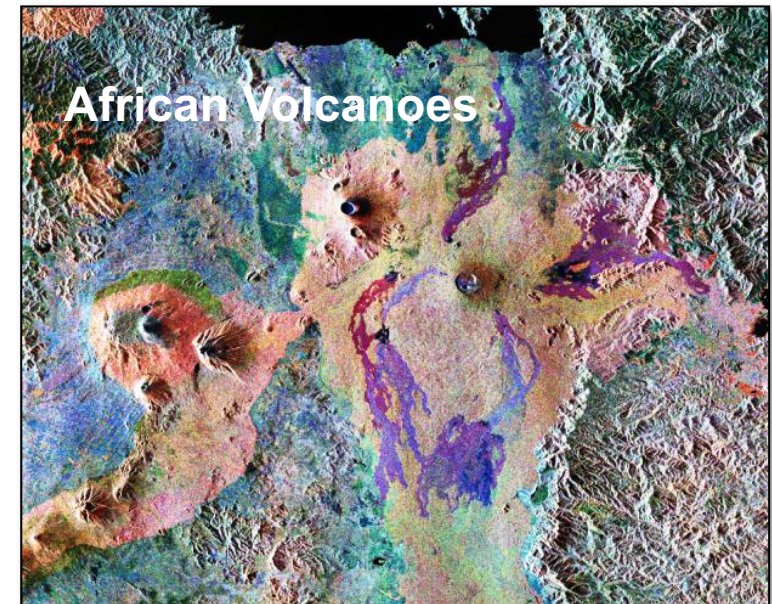
Radar Remote Sensors

- **Altimeters**
 - height of a surface
- **Sounders/Profilers**
 - volume composition and structure
- **Scatterometers**
 - surface composition and roughness
- **Synthetic Aperture Radar (SAR)**
 - surface composition and roughness imagery
- **Polarimeters**
 - improves surface or volume structure information
- **Interferometers**
 - topography and topographic change



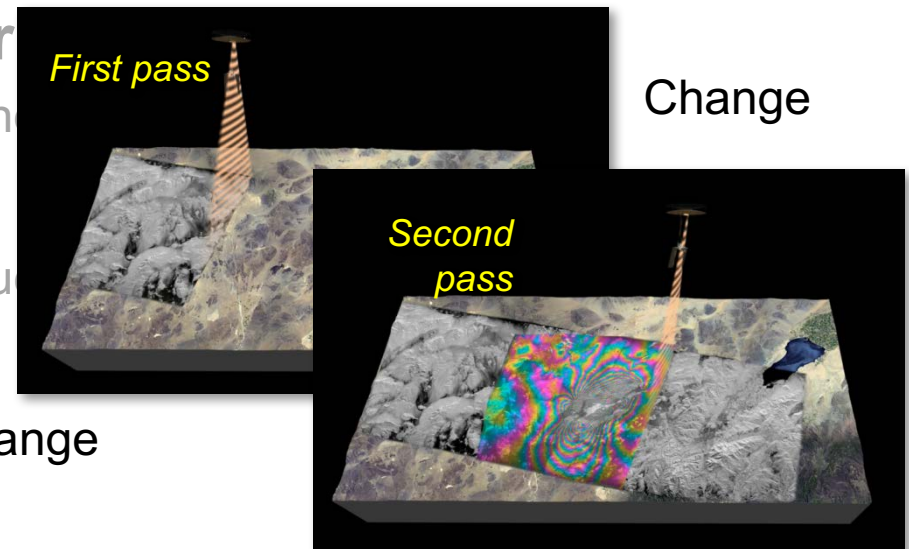
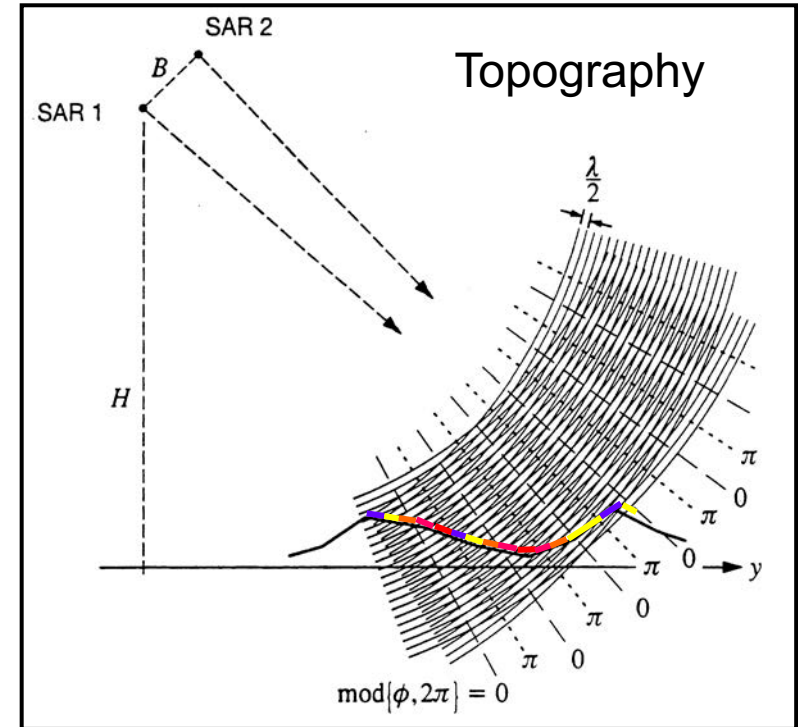
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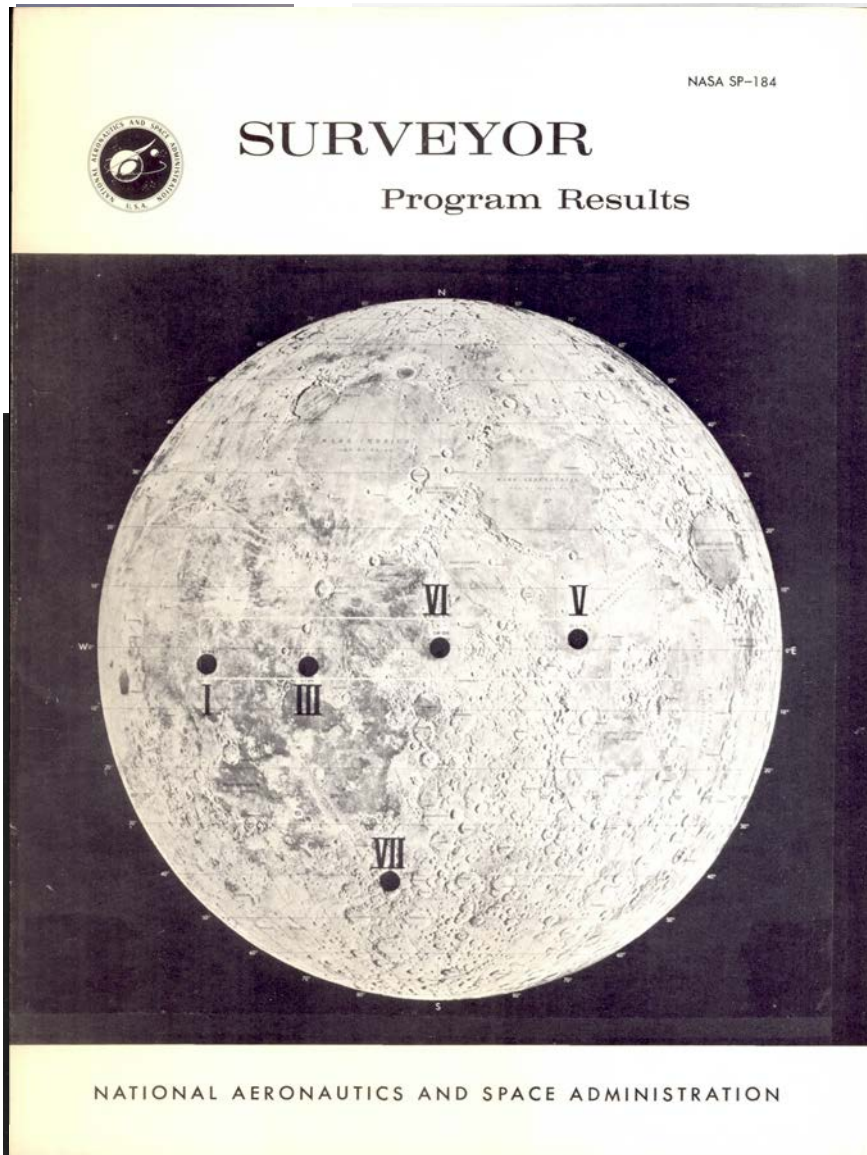


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Early JPL Radar Developments

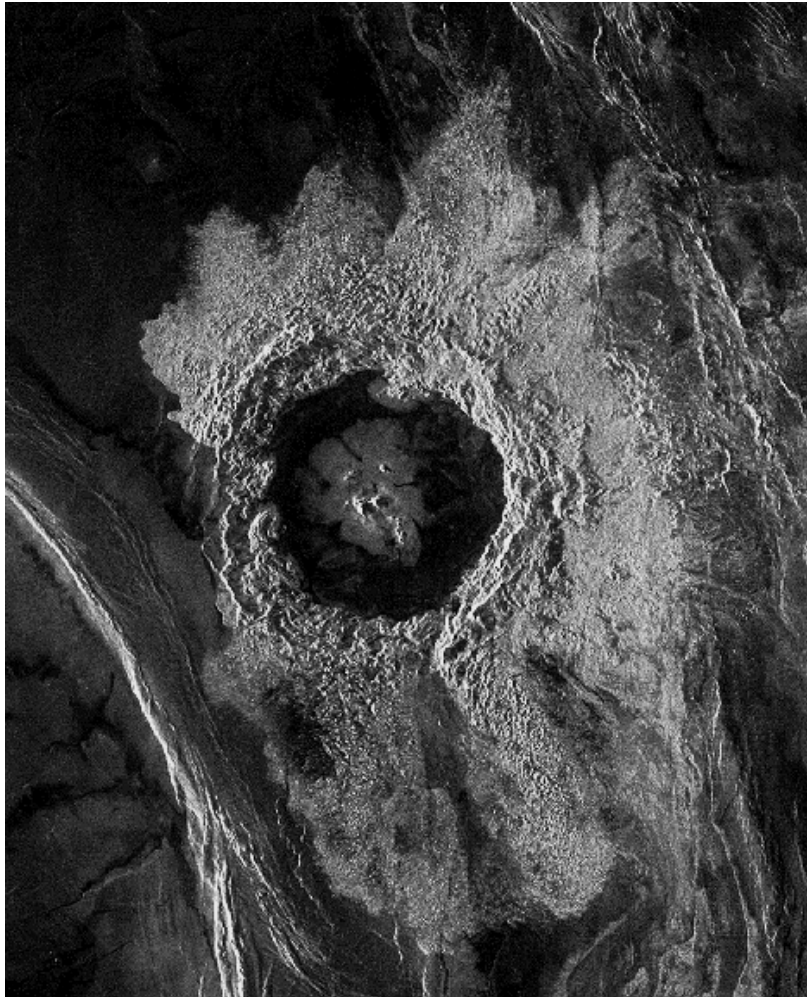


1970- LHH Airborne Radar Image of Death Valley

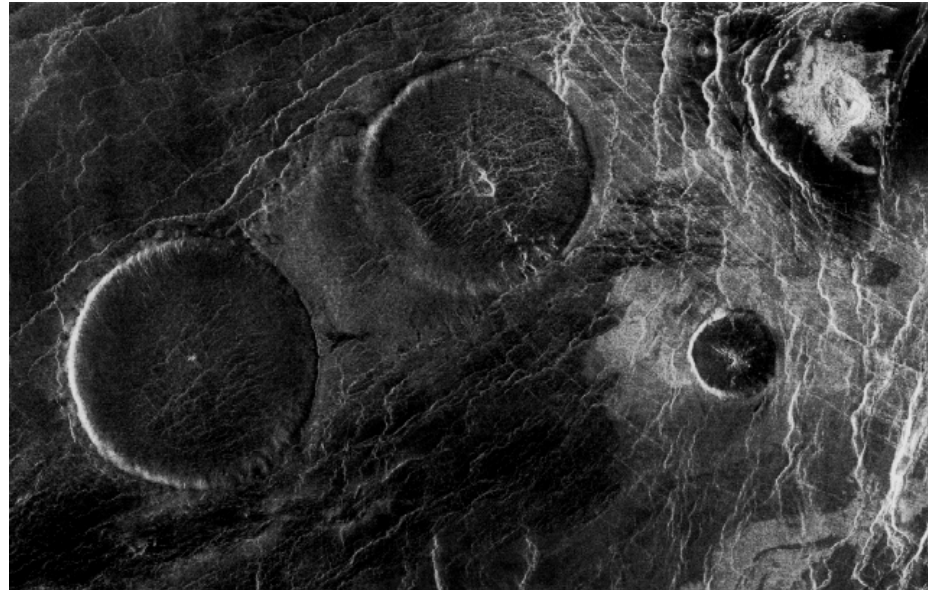
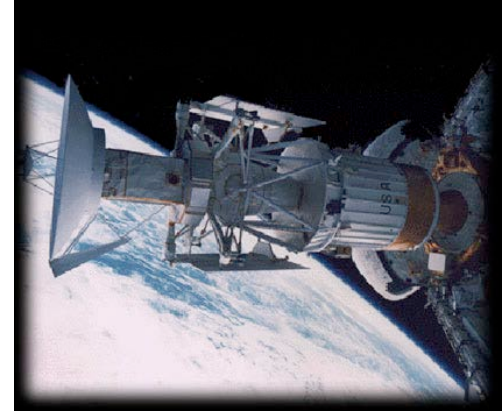


Magellan Radar To Venus

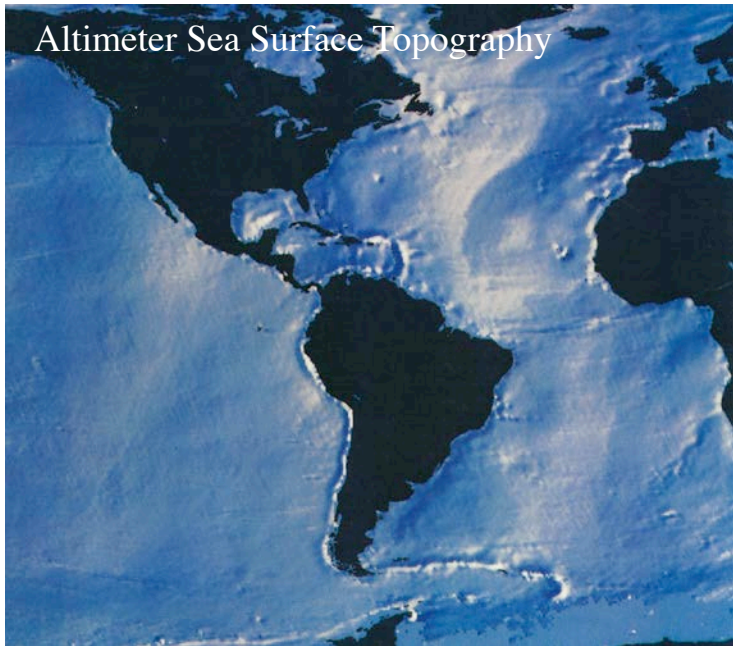
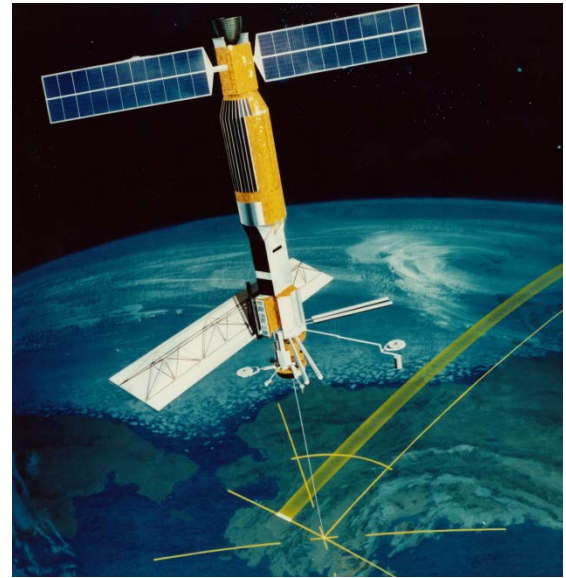
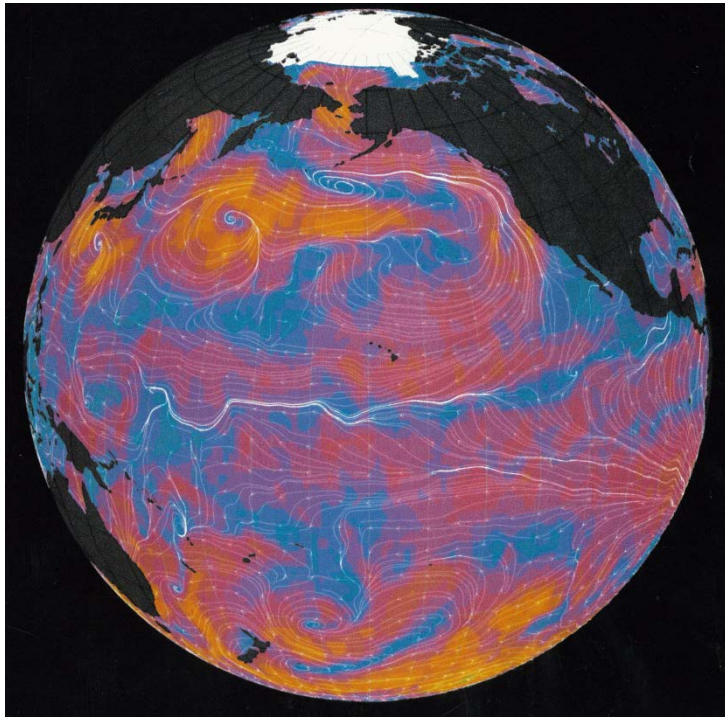
Magellan radar mapped 98% of the surface of Venus with an S-Band (12 cm) radar.



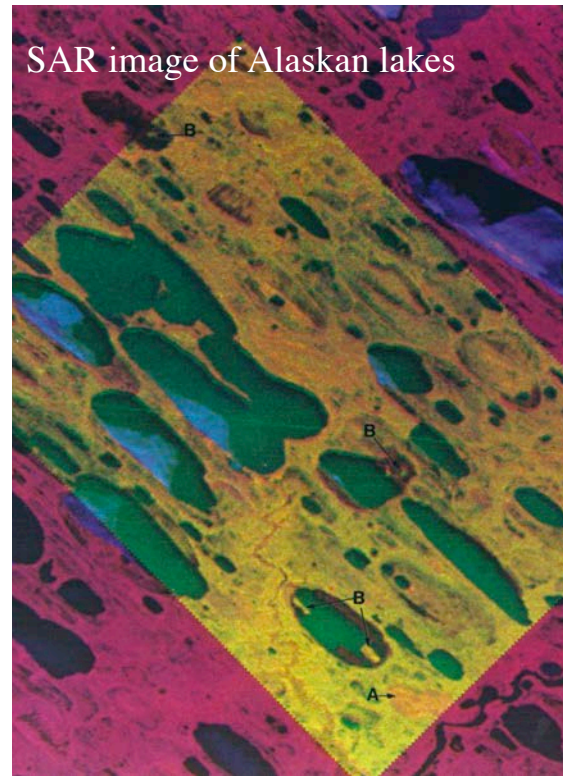
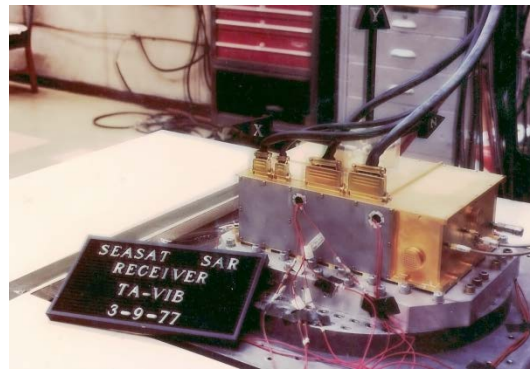
Impact Crater



Pancake Volcanoes



Altimeter Sea Surface Topography



SAR image of Alaskan lakes

SEASAT Capabilities

- Orbit - 800 km, 108° inclination, multiple phases, including initial mapping phase followed by 3-day exact repeat
- SAR - L-band, HH, 100 km, 25 m resolution, 100 km swath, fixed incidence angles 20-26°
- Altimeter – Ku-band (13.5 GHz), 1.7 km pulse limited footprint, 10 cm range resolution
- Scatterometer (SASS)– Ku-band (14.6 GHz), VV, HH, 50 range resolution, 2x500 km swath width
- Passive Microwave (SMMR) – 6.6, 10.7, 18, 21, 37, 600 km swath

SEASAT SAR Coverage

Fairbanks

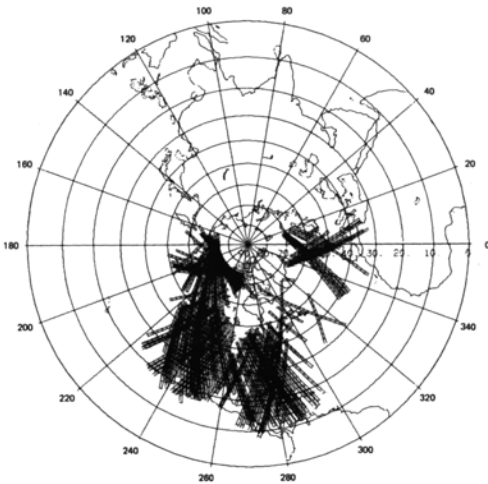


Figure A-1. Composite Seasat SAR areal coverage

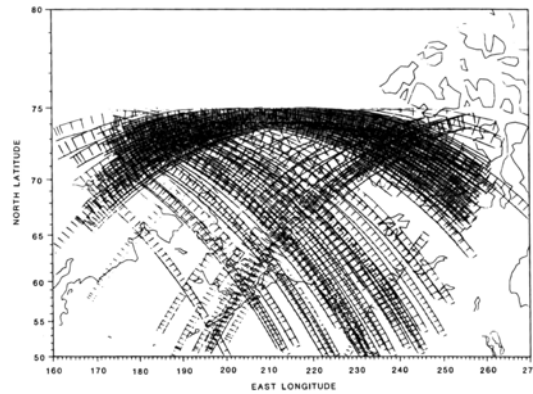


Figure A-14. Fairbanks, Alaska: July 4 through October 9, 1978

Goldstone

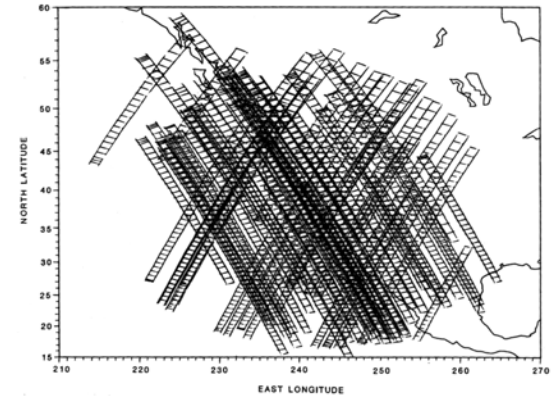


Figure A-2. Goldstone, California: July 4 through October 9, 1978

Merritt Island

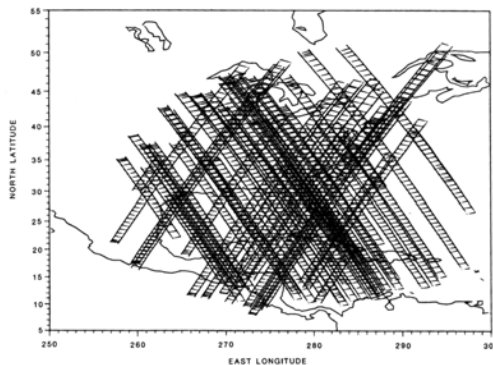


Figure A-8. Merritt Island, Florida: July 8 through October 9, 1978

Shoe Cove

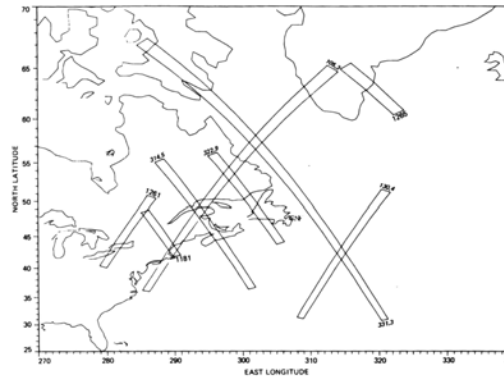


Figure A-13. Shoe Cove, Newfoundland: September 17 through October 9, 1978

Oakhanger

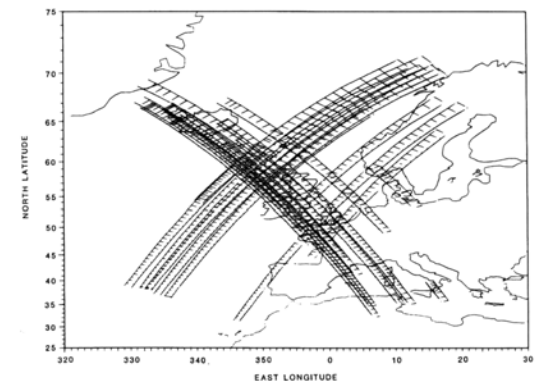


Figure A-24. Oakhanger, England: August 4 through October 10, 1978

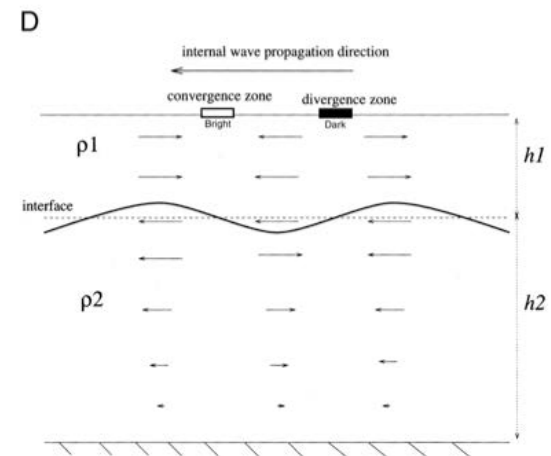
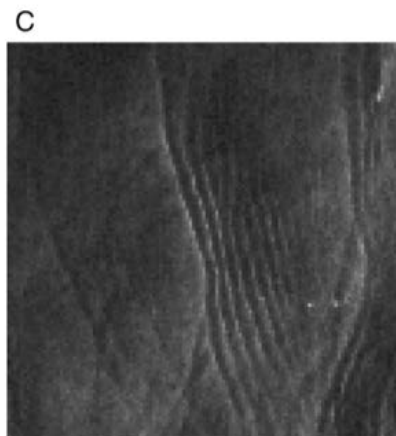
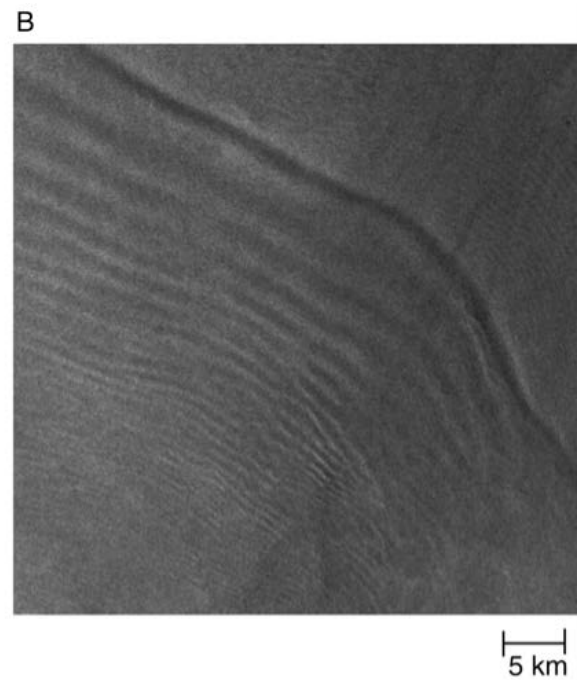
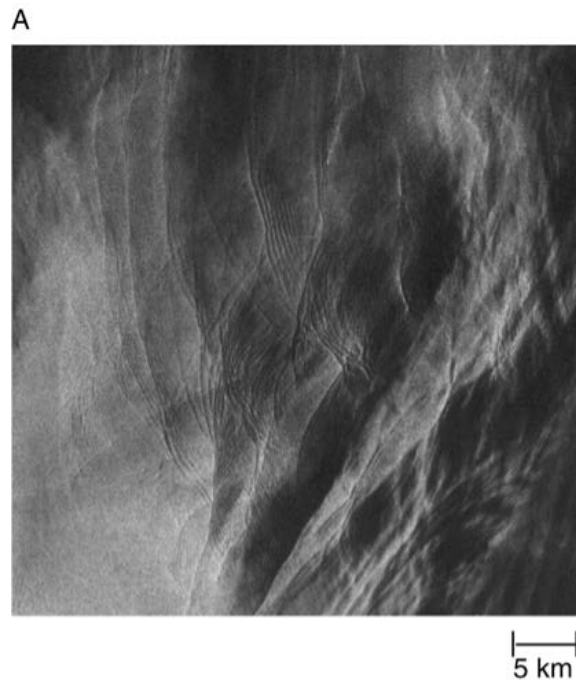
48 hours data collected, July to October, 1978

SEASAT SAR

Internal Waves

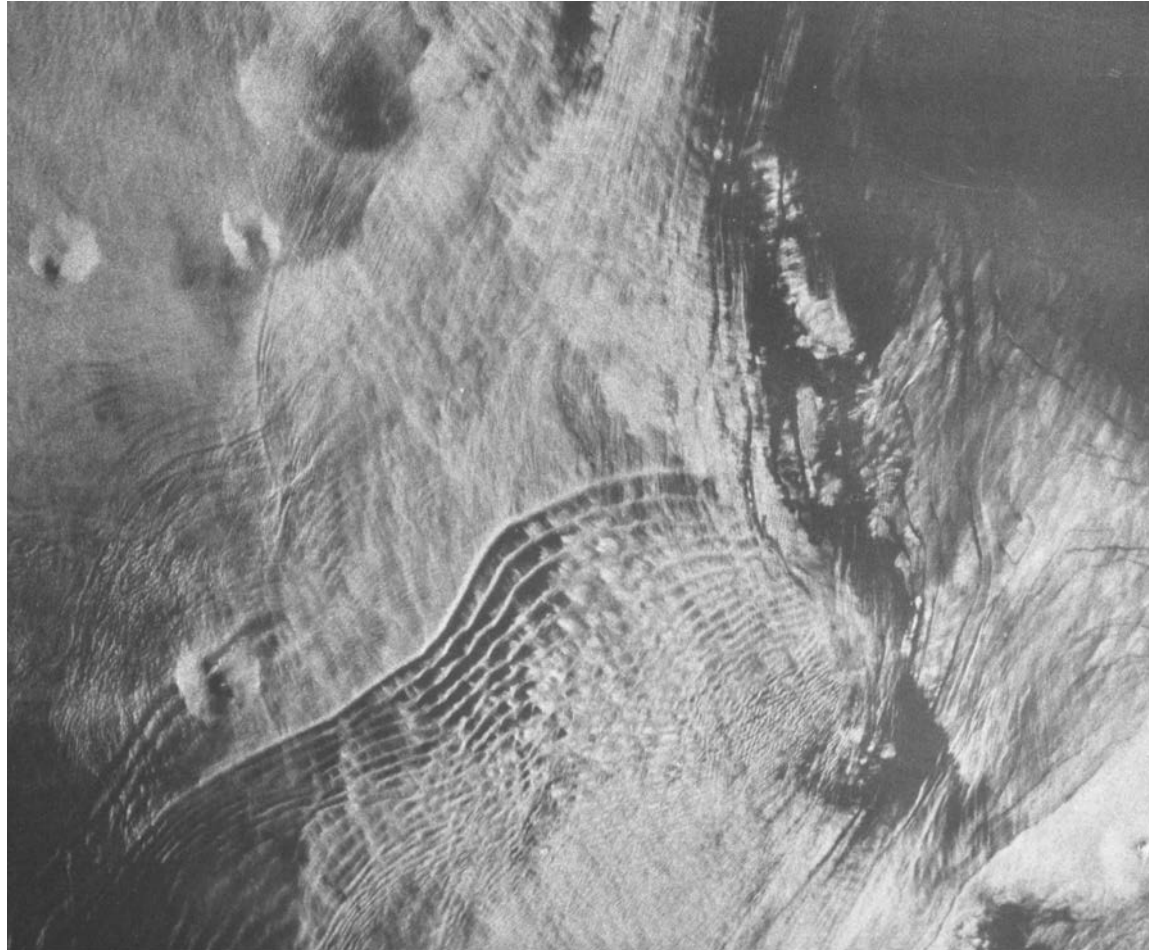
A/C New York Bight

B. Baffin Bay



SEASAT SAR – Gulf of Mexico

Internal waves, tropical rain cells, current flow, eddy



10 km

SEASAT SAR

Ice Motion Pair – Beaufort Sea

October 5, 1978

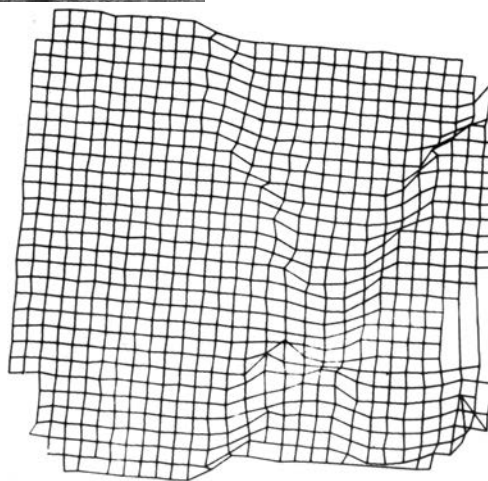


October 8, 1978



Deformation grid
showing areas of
Motion and NO
Motion

Quantifies opening &
closing, key for
heat flux estimates



Provided clear unambiguous
measurement and led to
development of first SAR
geophysical product using
ERS-1 SAR obtained
at NASA-supported
Alaska SAR Facility

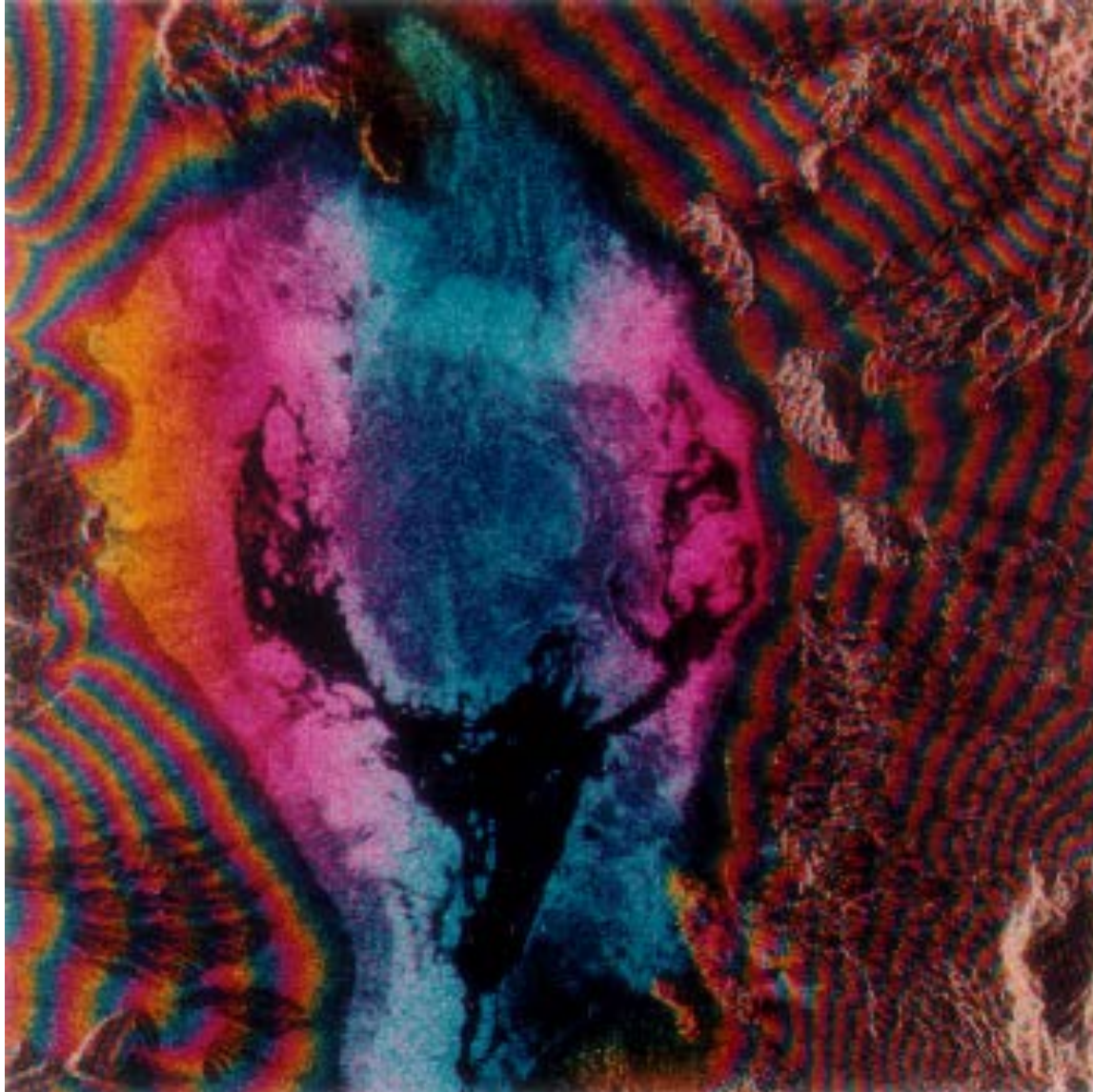
SEASAT

The genesis of Spaceborne SAR for Earth Science Death Valley (USA) 1978



SEASAT InSAR image of Death Valley

First demonstrations of interferometry from space

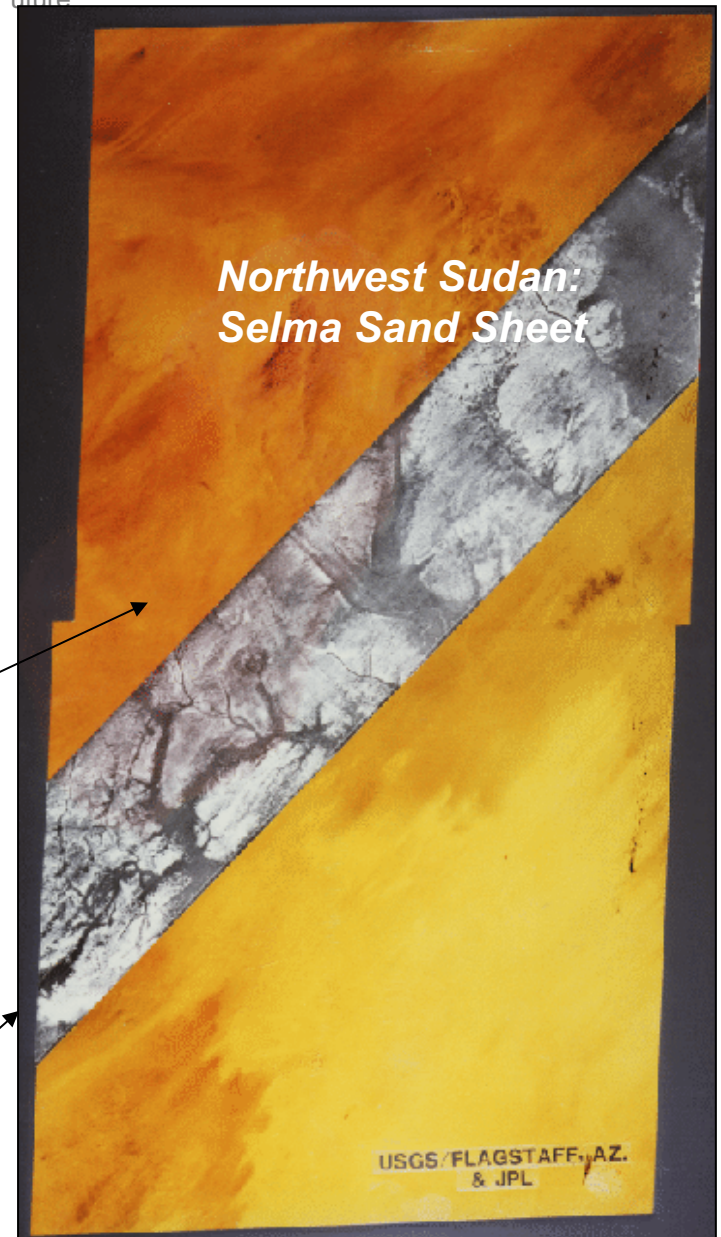


Shuttle Imaging Radar-A

- Radar at microwave wavelengths interact with the *geometric* and *electrical* properties of surfaces
- Radar observations allow us to experience the Earth in a fundamentally different light, day or night
- Radar at typical wavelengths can penetrate cloud cover

L-band (24 cm) SAR
Shuttle Imaging Radar-A

Optical



Shuttle Imaging Radar-C

- Demonstrated most currently exploited phenomenology and techniques*

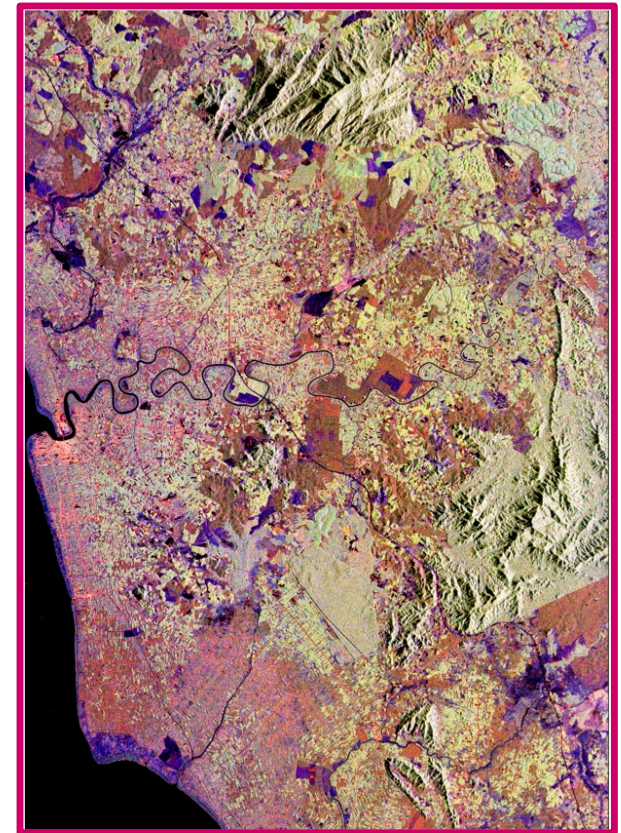


**Wheat Fields,
Dnieper
River, Ukraine**

**Red: LHH
Green: LHV
Blue: CHV**

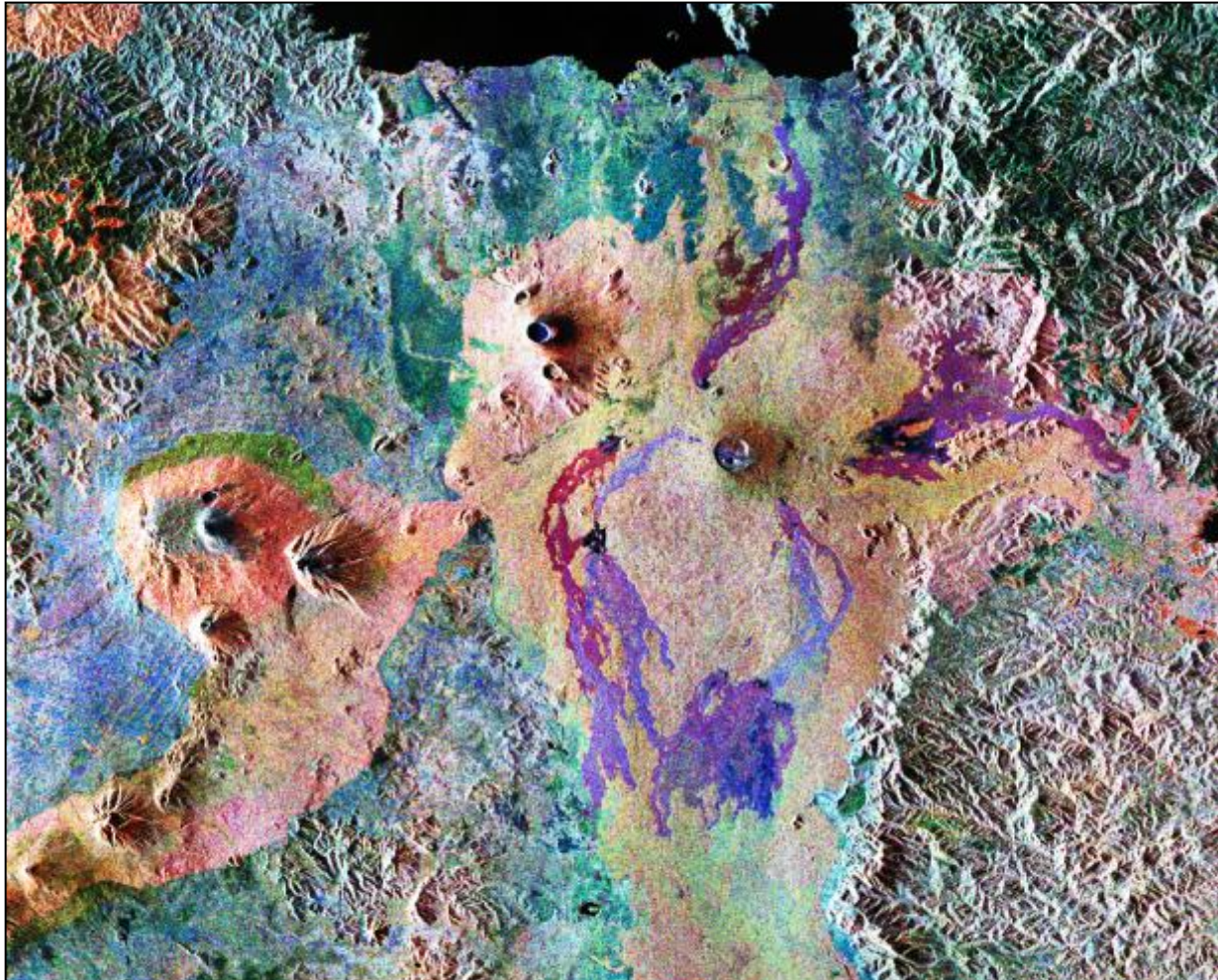
**Rubber,
banana, and
oil palm trees,**

**Muar,
Malaysia**



Examples of dual-frequency measurements from SIR-C/X-SAR

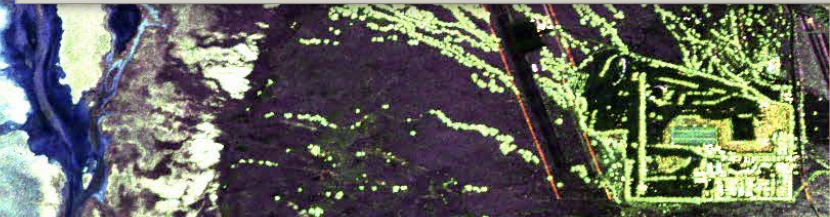
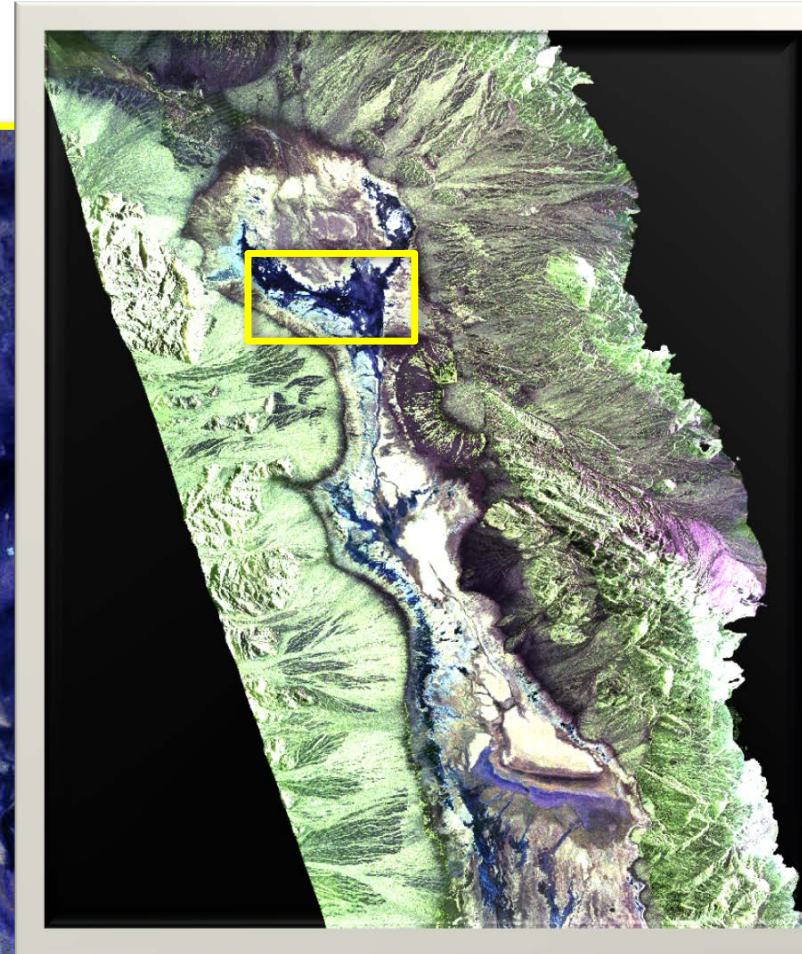
SIR-C/X-SAR: Characterizing the Earth's Surface



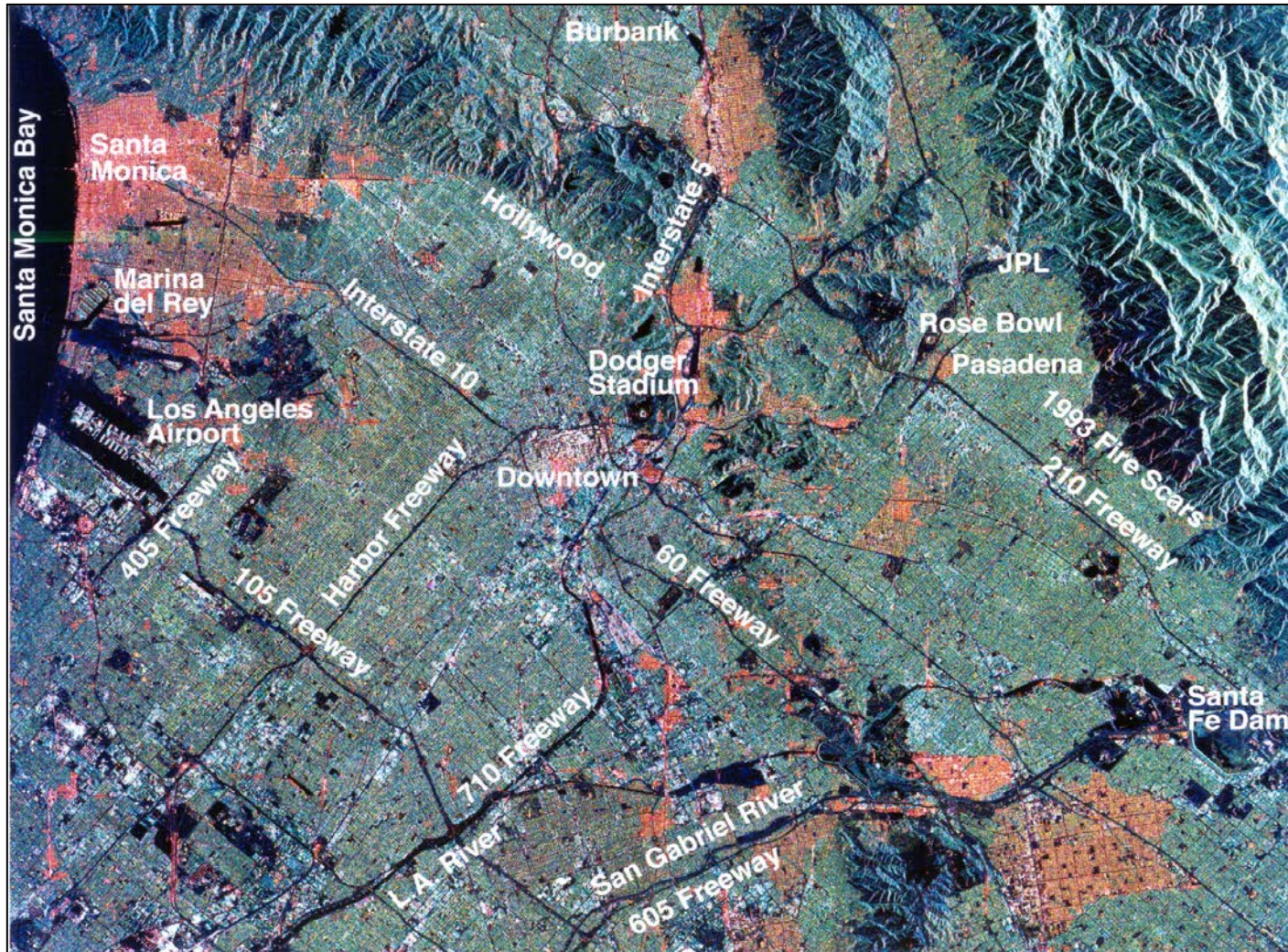
Rwanda/Uganda Volcanoes

Polarimetric SAR at Death Valley

(HH-Red, HV – Green, VV – Blue)

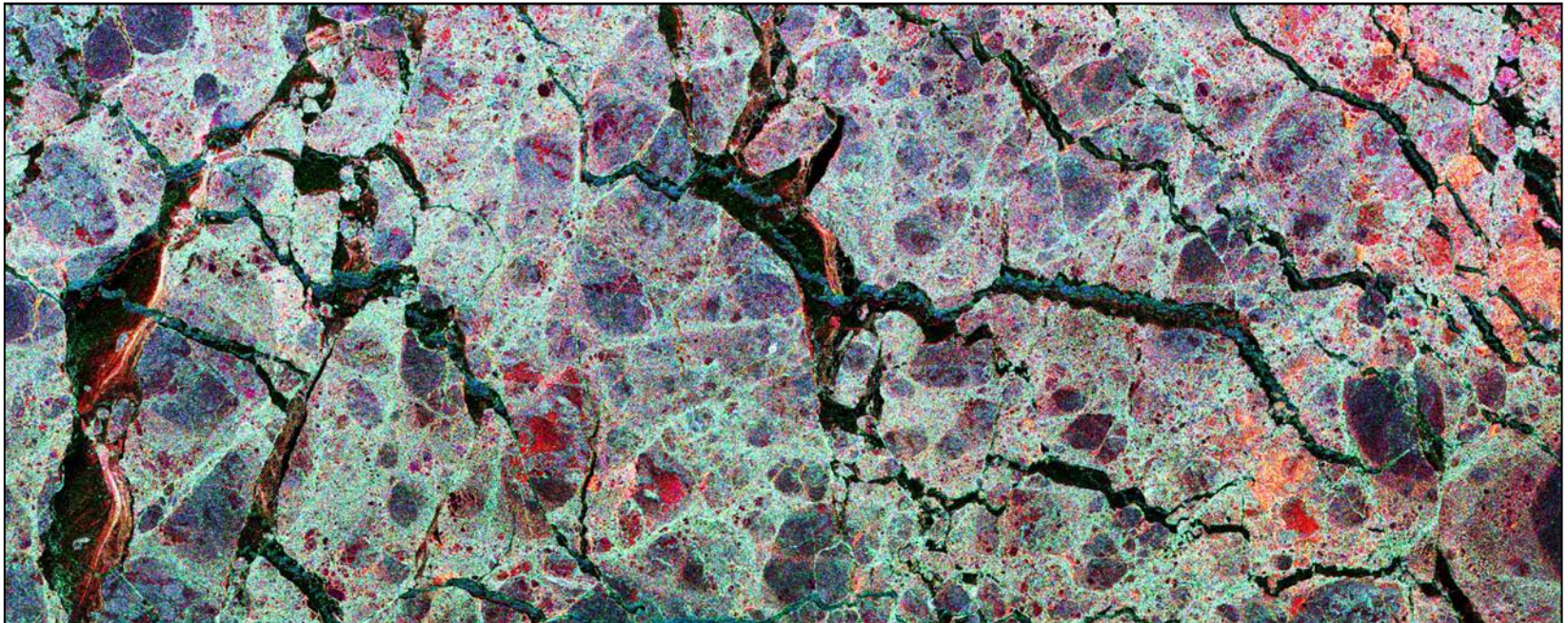


Polarimetry from SIR-C/X-SAR



SIR-C/X-SAR Views Sea Ice

Multi-frequency, multi-polarization radar can measure the extent, thickness and morphology of the polar ice pack.



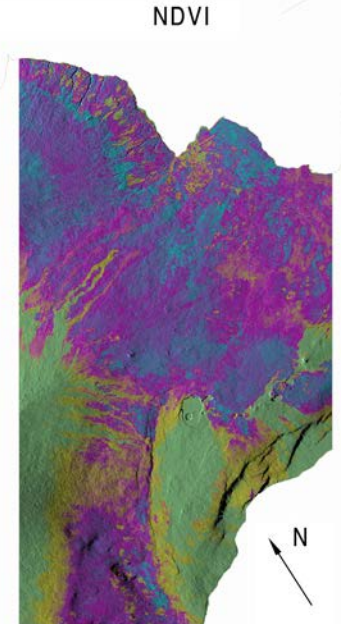
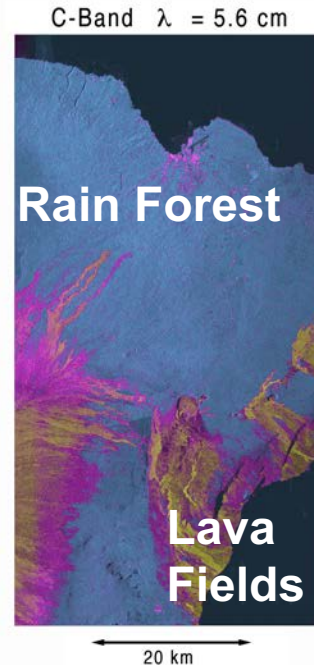
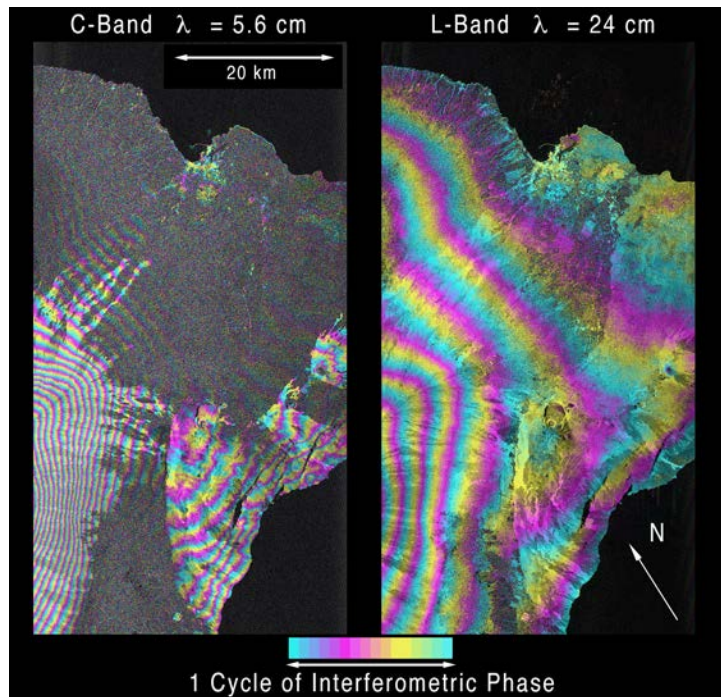
Weddell Sea, Antarctica

Red: CHH Green: LHV Blue: LHH

SIR-C L and C-band Interferometry

6 month time separated observations to form interferograms
Simultaneous C and L band (Rosen et al. 1996)

Big Island, Hawaii

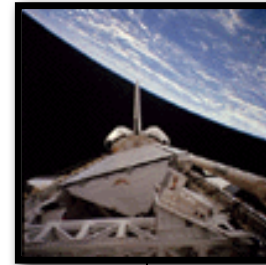


InSAR experiments have shown good correlation at L-band

JPL Coupled Airborne and Spaceborne SAR Programs



Rocket Radar mounted on NASA CV-990. (L-band only.)

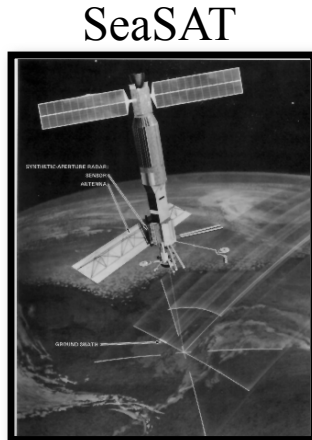


SIR-C



IFSARE/*3I

Rocket Radar

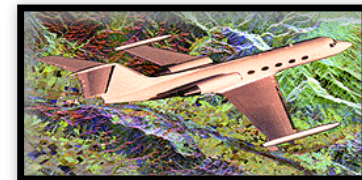


SeaSAT

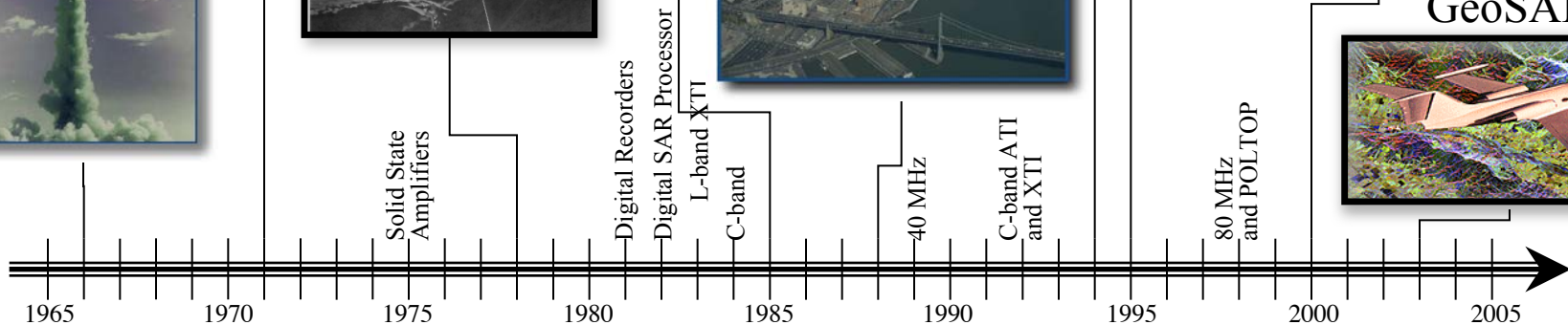
AIRSAR re-built on DC-8



SRTM



GeoSAR



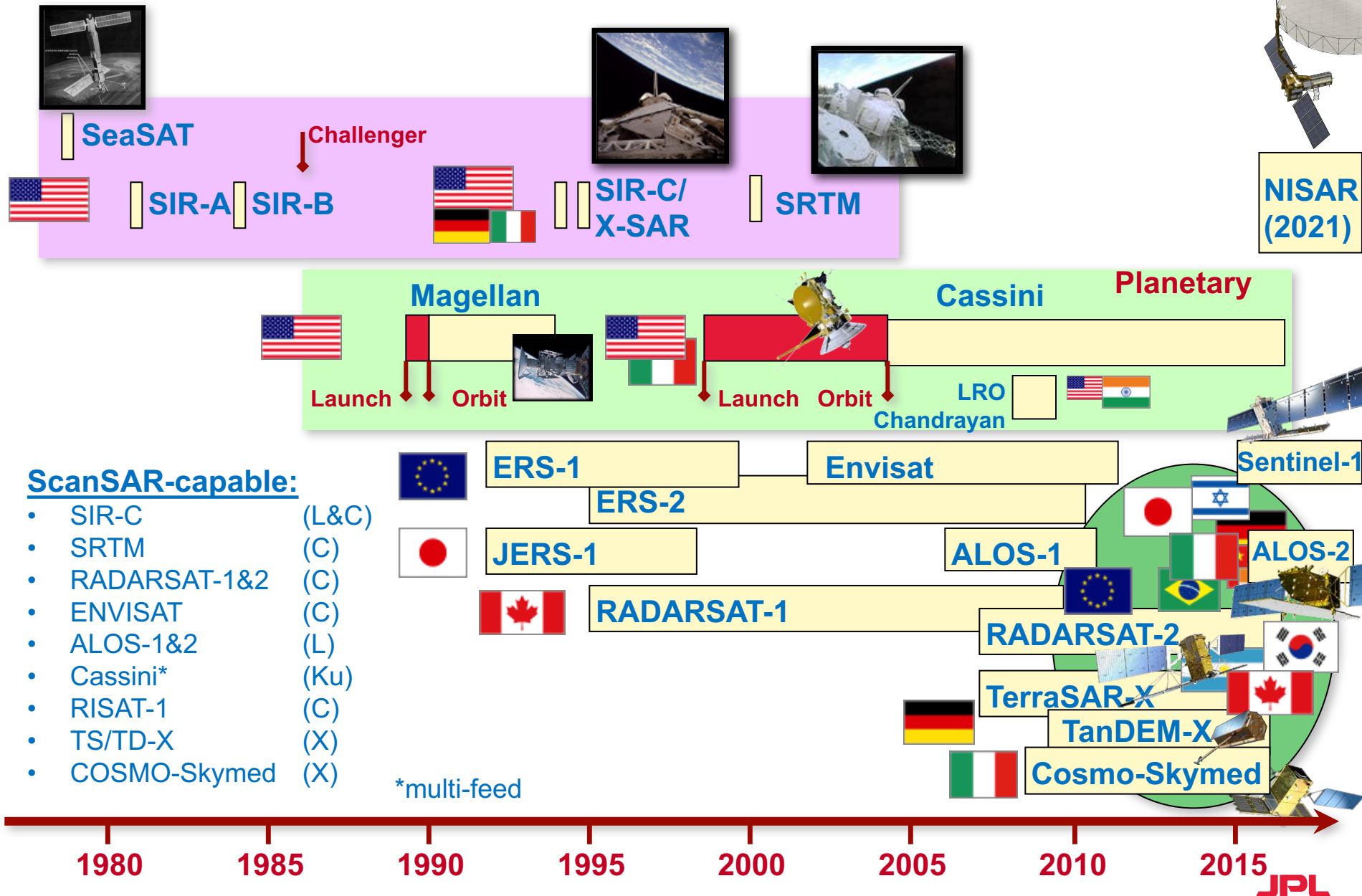
San Joaquin Valley, California

Soil moisture estimation, vegetation classification

(HH-Red, HV – Green, VV – Blue)

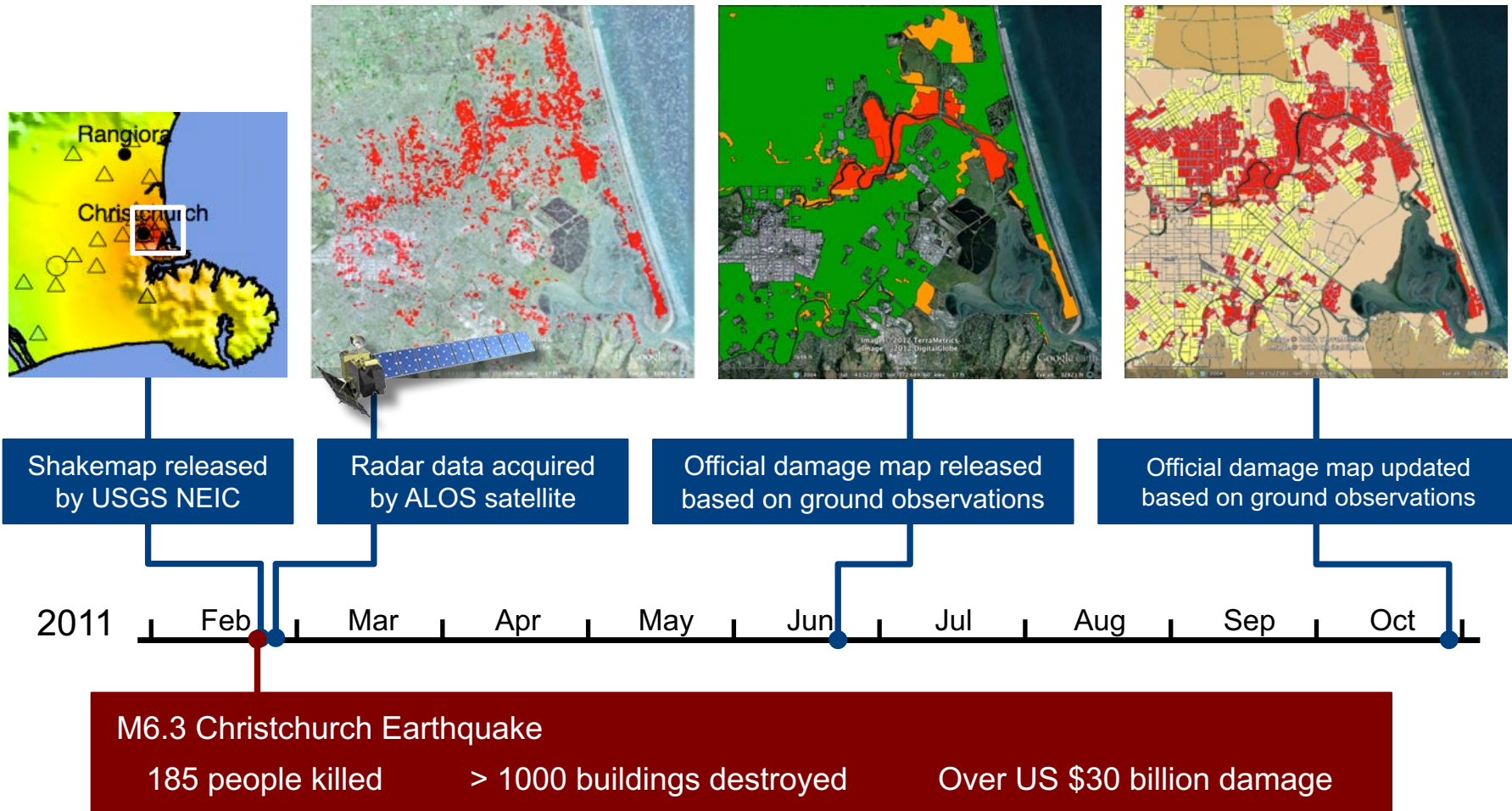


International SAR Missions



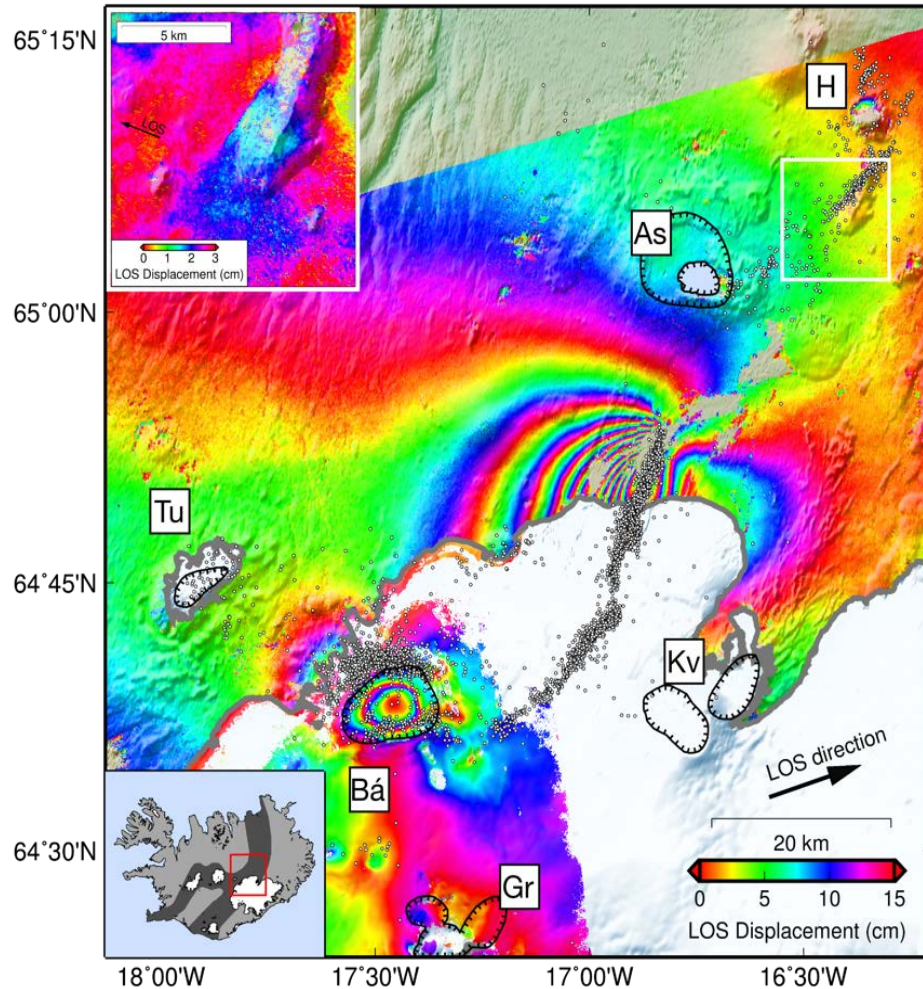
Application to Improve Disaster Response

Damage Proxy Map from radar data



Fast sampling permits imaging dynamics

COSMO-SkyMed (1-day) fills in Radarsat-2 (24-day) pairs

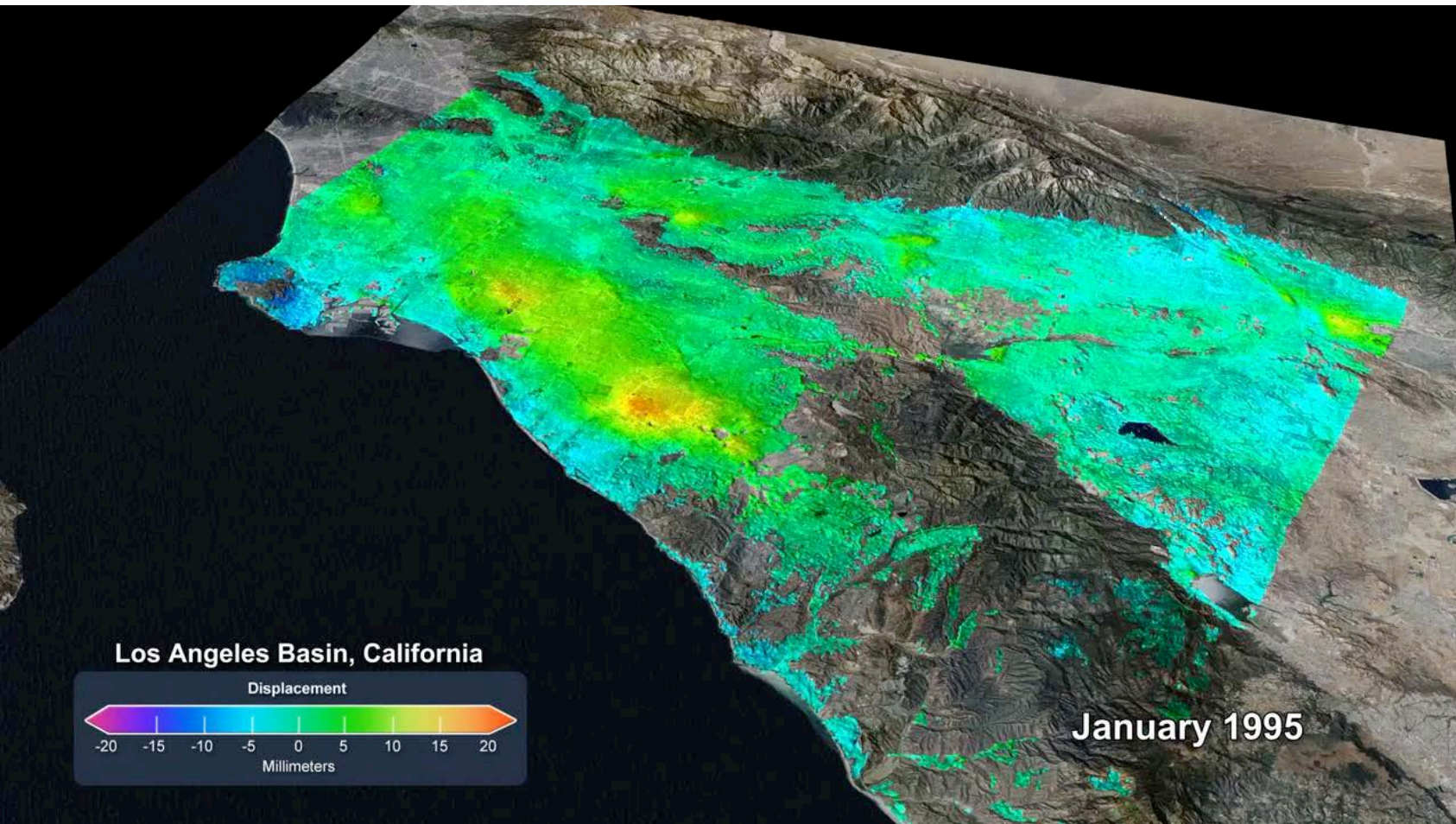


Collapse of Bárðunga Caldera (Iceland) & associated plate boundary rifting

Riel et al., *Geophys. J. Int.*, 2015

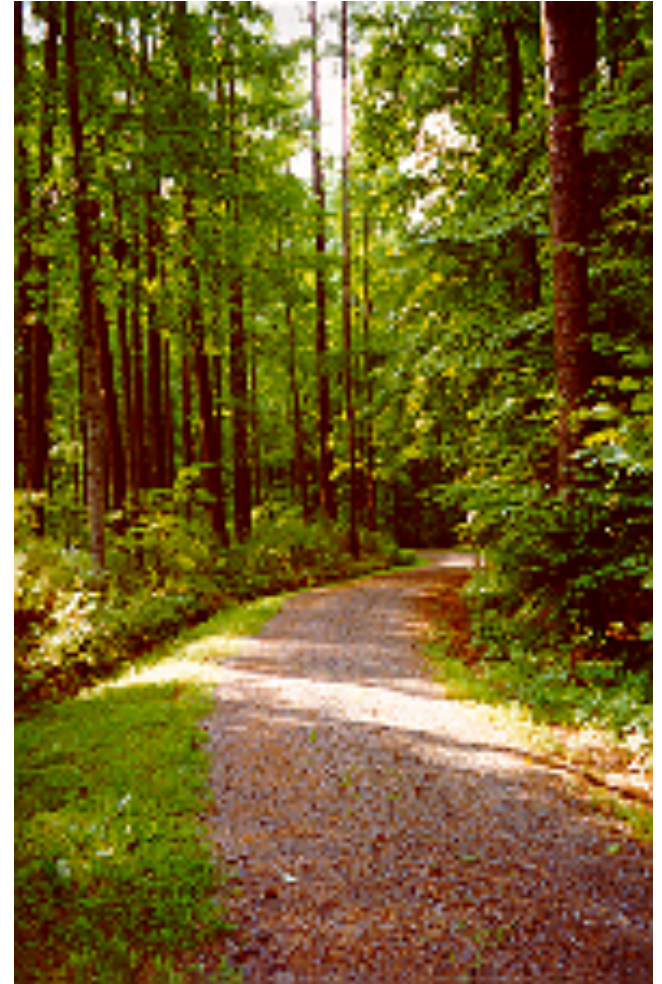
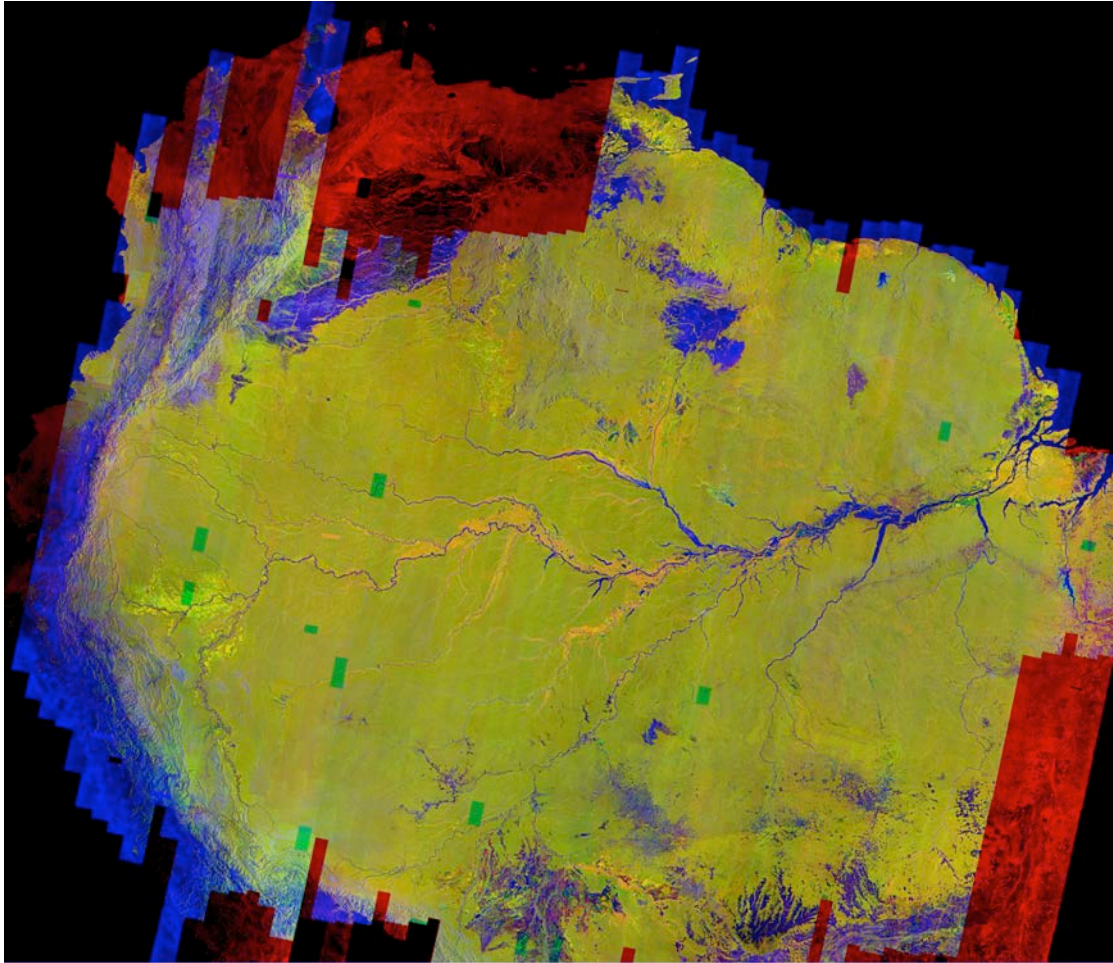
Measuring Aquifer Usage In Los Angeles

Surface Deformation from ERS and Envisat time series



Measuring the Global Terrestrial Carbon Cycle

ALOS PALSAR (L-Band)



Courtesy P. Siqueira, U. Mass Amherst

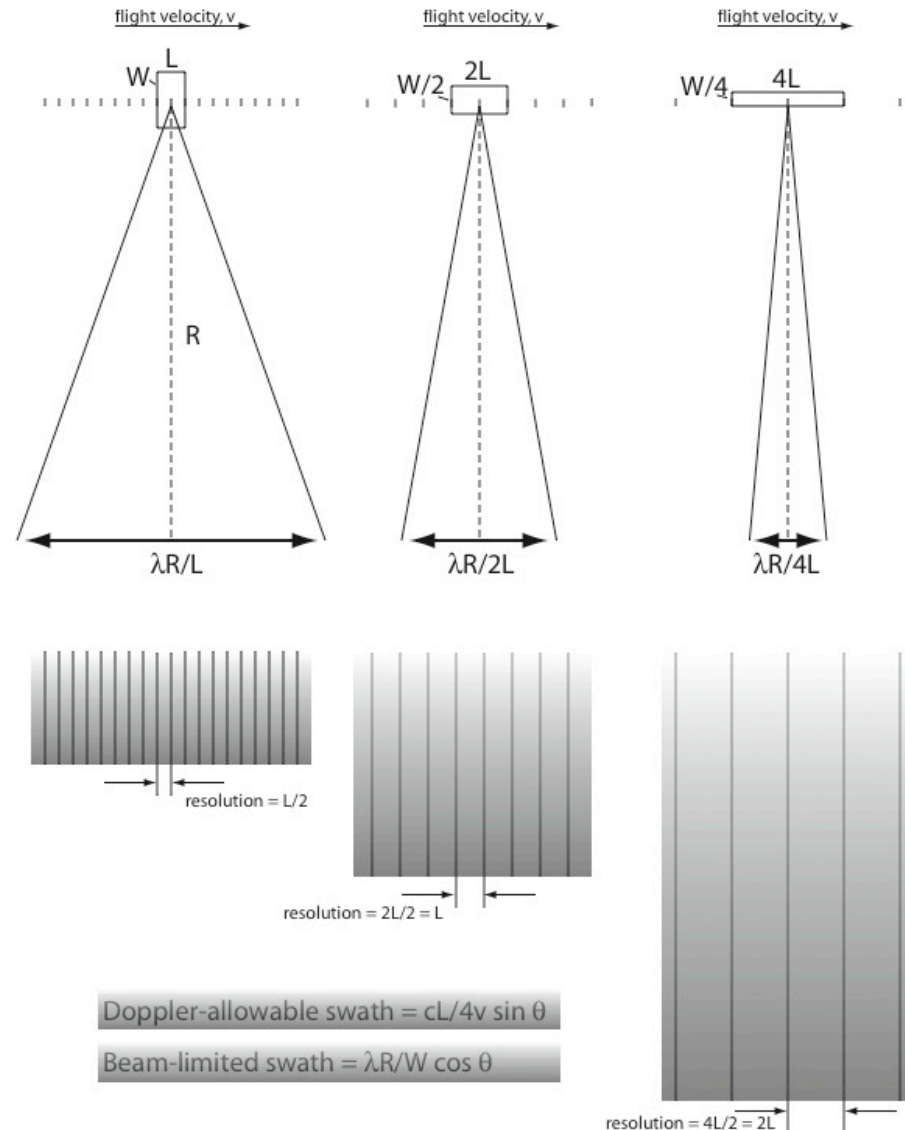
User Needs Drive Remote Sensing System Design Characteristics

User	Application	Characteristic*
Commercial	Infrastructure Monitoring	Targeted Area Fast Revisit Global Accessibility Fine Resolution
Operational	Disaster Monitoring Inventory Monitoring Ship/Vehicle Tracking	Broad Areas Fast Revisit Global Accessibility Fine-Moderate Resolution
Earth Science	Dynamic process studies Global inventories	Global-scale areas Fast Revisit Global Accessibility Moderate-Low Resolution Open Access

*representative characteristics – exceptions abound

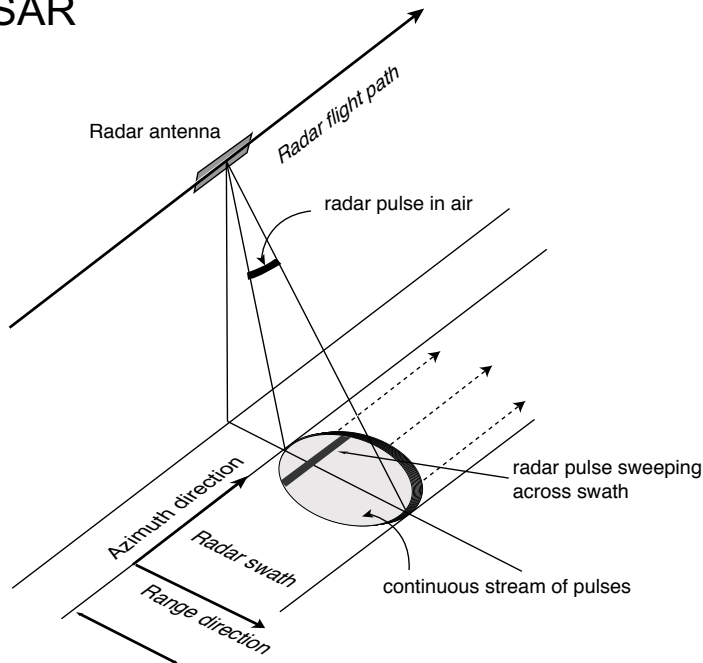
SAR Ambiguities and Antennas

- Antenna area essentially determines the data rate and ambiguities
- Antenna length determines azimuth resolution $L/2$
- For conventional SAR, only one transmission in the beam at a time to avoid range ambiguities
 - ⇒ For a given antenna length, elevation size must be large enough to restrict swath



Homage to Richard Moore and Kiyo Tomiyasu: Wide Swath SAR

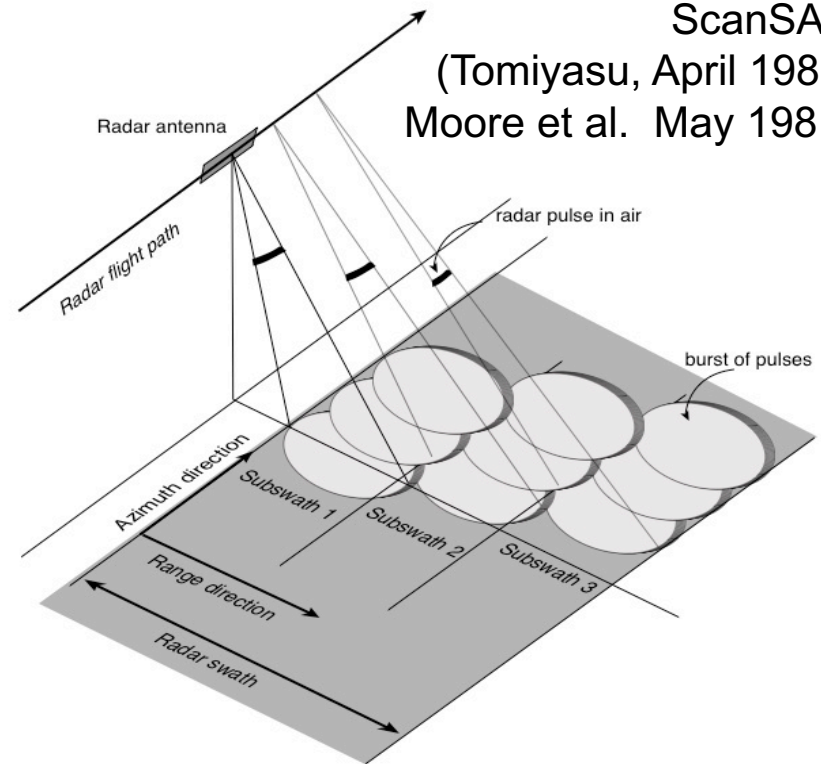
StripSAR



- “Dedicated” synthetic aperture in fixed beam for nominal swath and resolution

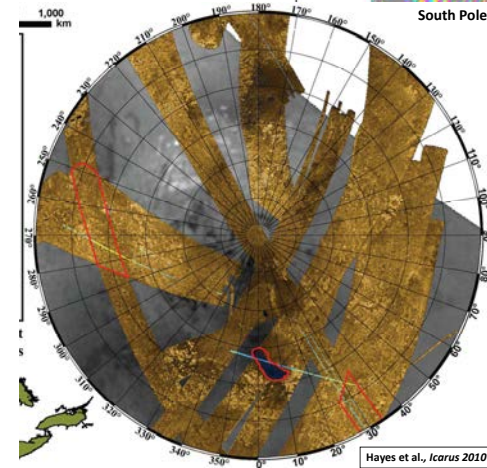
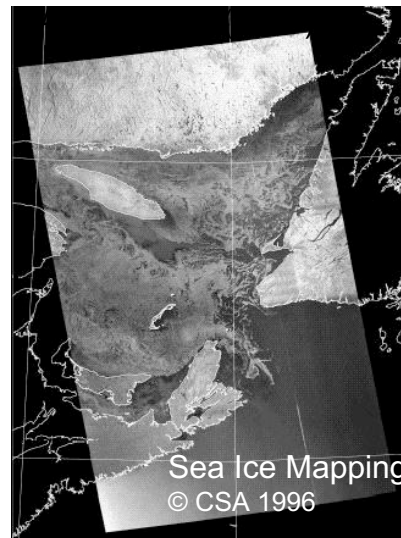
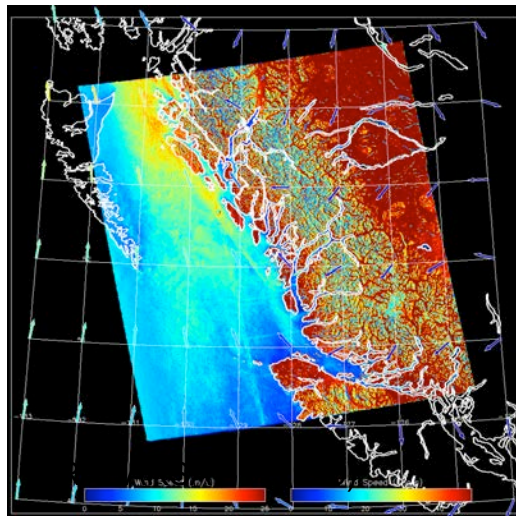
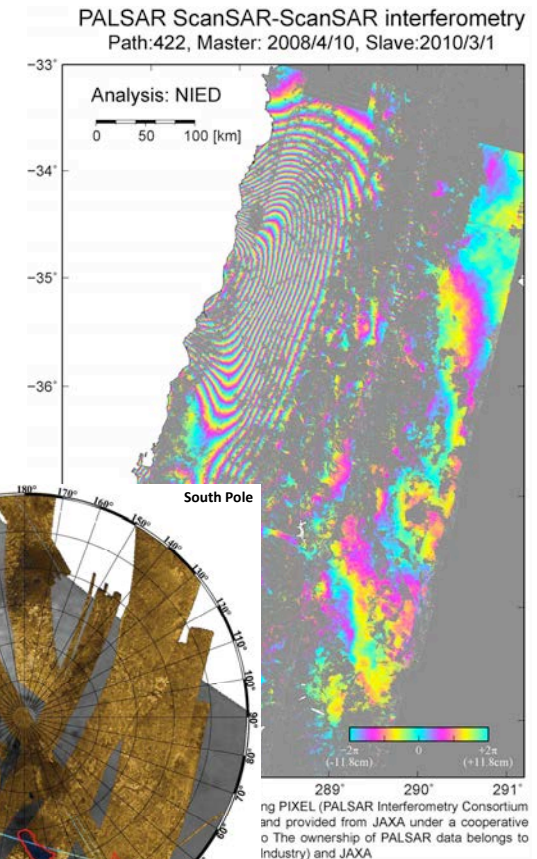
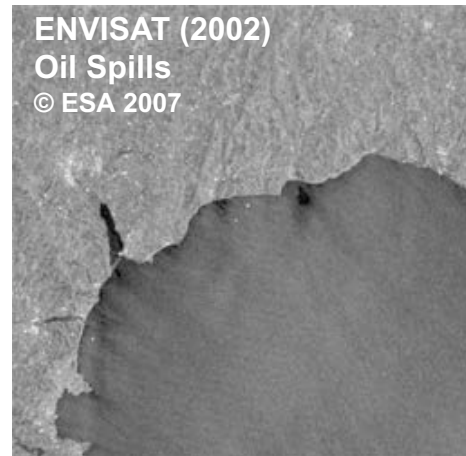
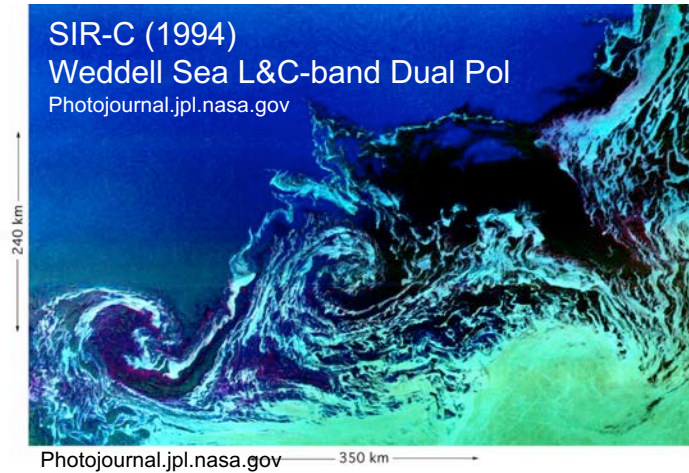
ScanSAR

(Tomiyasu, April 1981;
Moore et al. May 1981)



- Time-share synthetic aperture among elevation beams to increase swath
- Degraded azimuth resolution

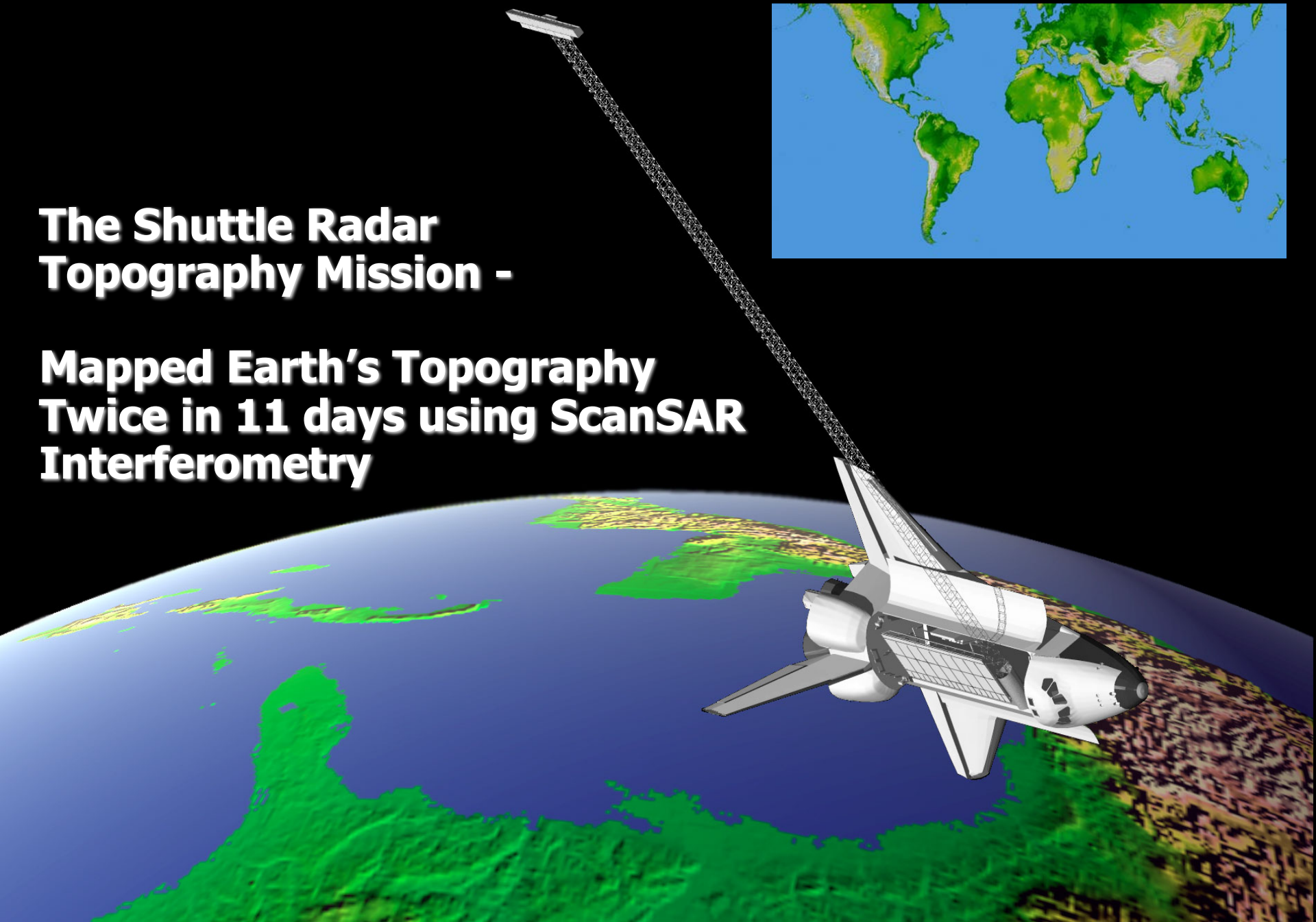
ScanSAR Imagery Examples



Cassini

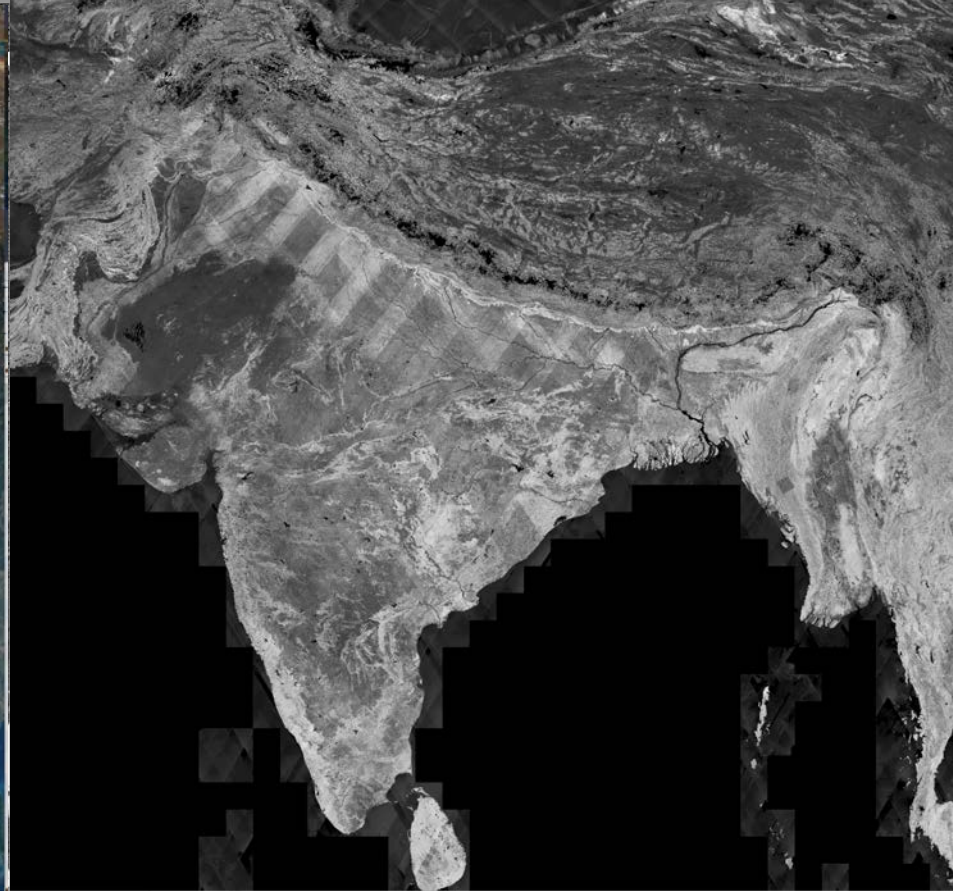
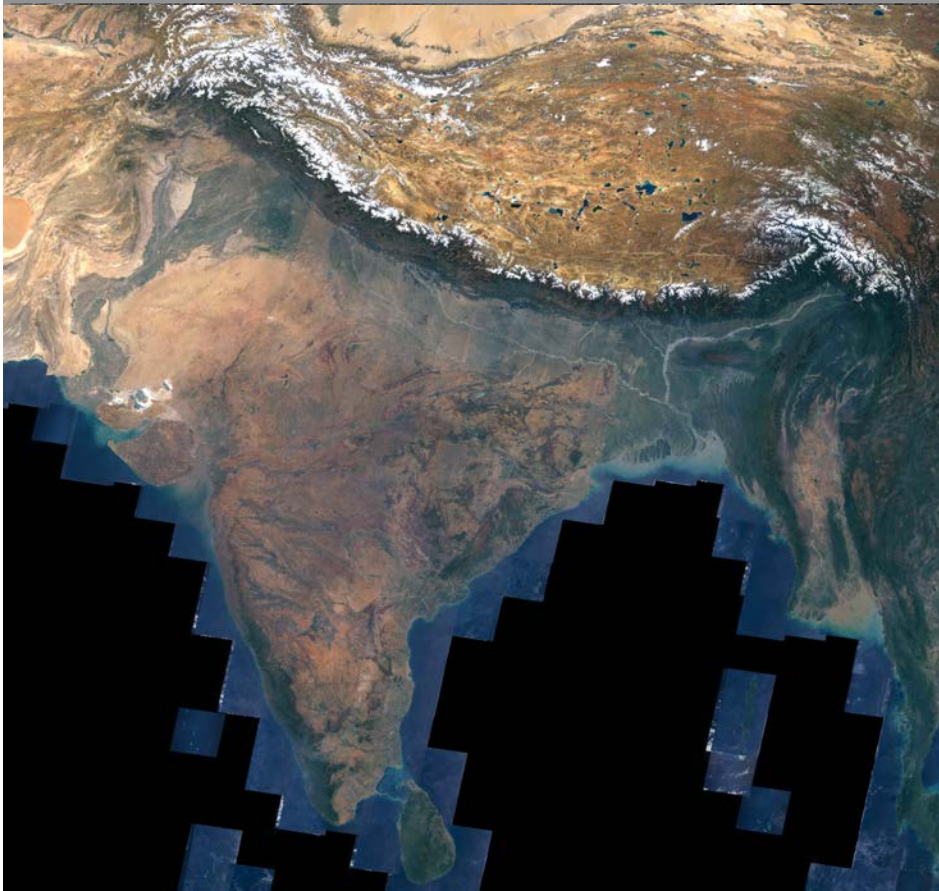
The Shuttle Radar Topography Mission -

**Mapped Earth's Topography
Twice in 11 days using ScanSAR
Interferometry**



SRTM Views India

Landsat 150 m Resolution Mosaic

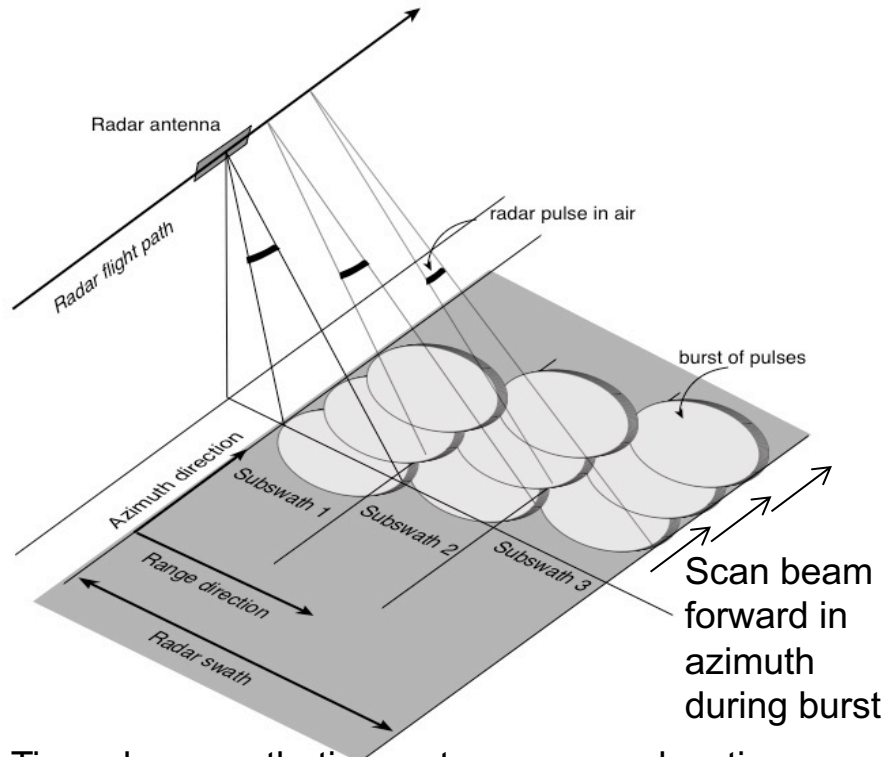


SRTM 150 m Resolution Topography Mosaic Shaded Relief February 2000

SRTM 150 m Resolution Image Mosaic C-band February 2000

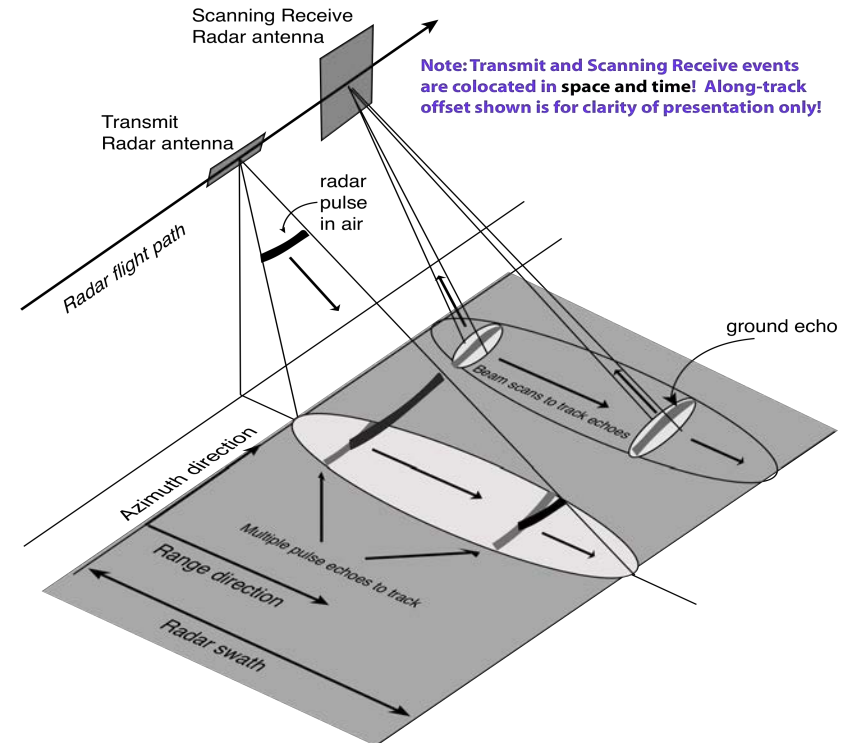
Toward Full Resolution and Wide Swath SAR

Terrain Observation by Progressive Scan



- Time-share synthetic aperture among elevation beams to increase swath
- Scan beam forward in azimuth within burst to improve radiometry
- Degraded azimuth resolution

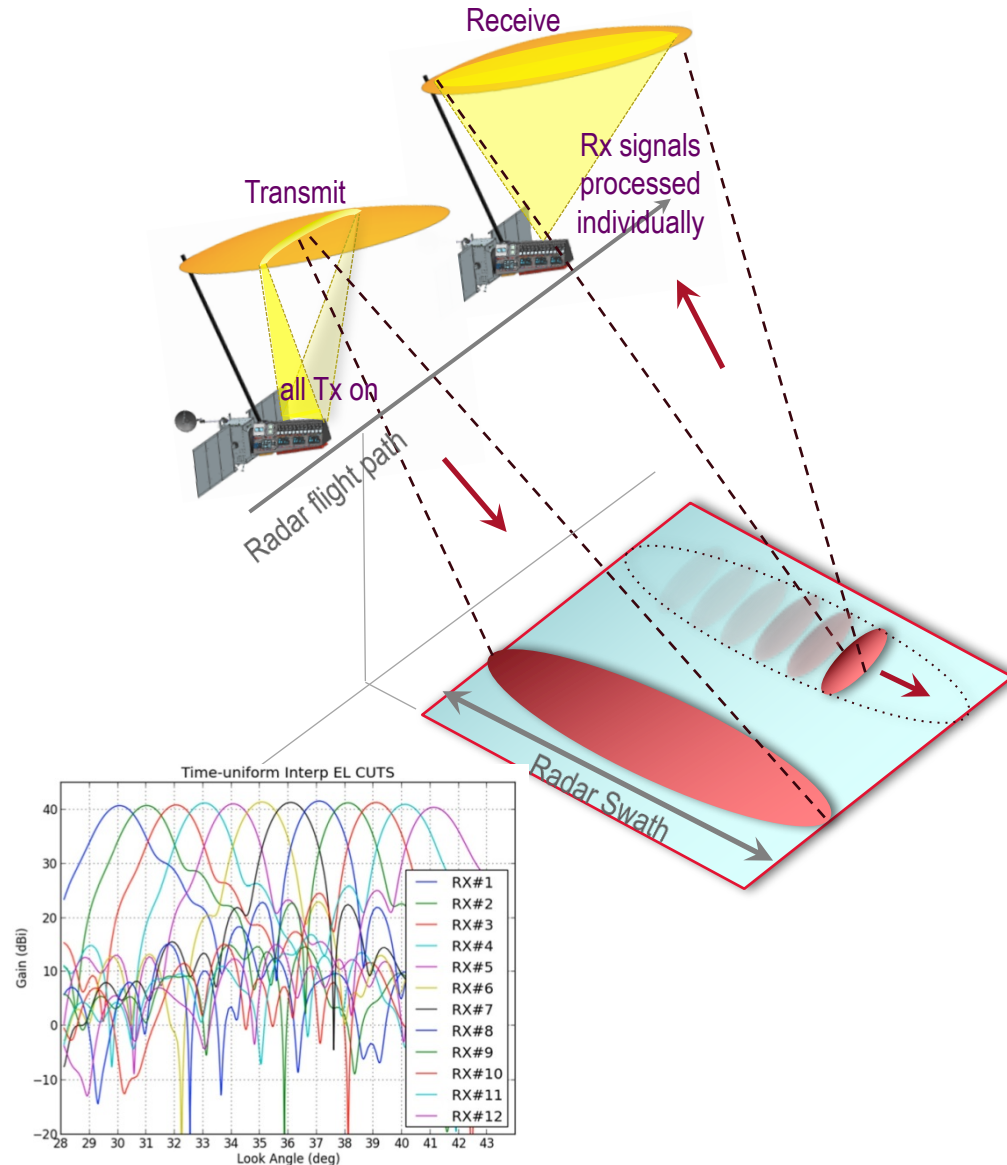
Scan on Receive SAR (SweepSAR)



- Time-share pulse returns on receive with multiple receive beams to increase swath
- Track receive echoes as they propagate across the swath
- Narrow receive beam controls ambiguities

SweepSAR Achieves Wide Swath

- The SweepSAR technique is a means to achieve wider swath than stripmap SAR, without the performance compromises of ScanSAR
- Features of the SweepSAR technique implemented with an array-fed reflector antenna:
 - On transmit, all feed array elements are illuminated (*maximum transmit power*), creating the wide elevation beam
 - On receive, the feed array element echo signals are processed individually, taking advantage of the large-area reflector for each beam *to maximum antenna gain*
 - Uses *digital beamforming (DBF)* on receive to allow multiple simultaneous echoes in the swath to be resolved by angle of arrival



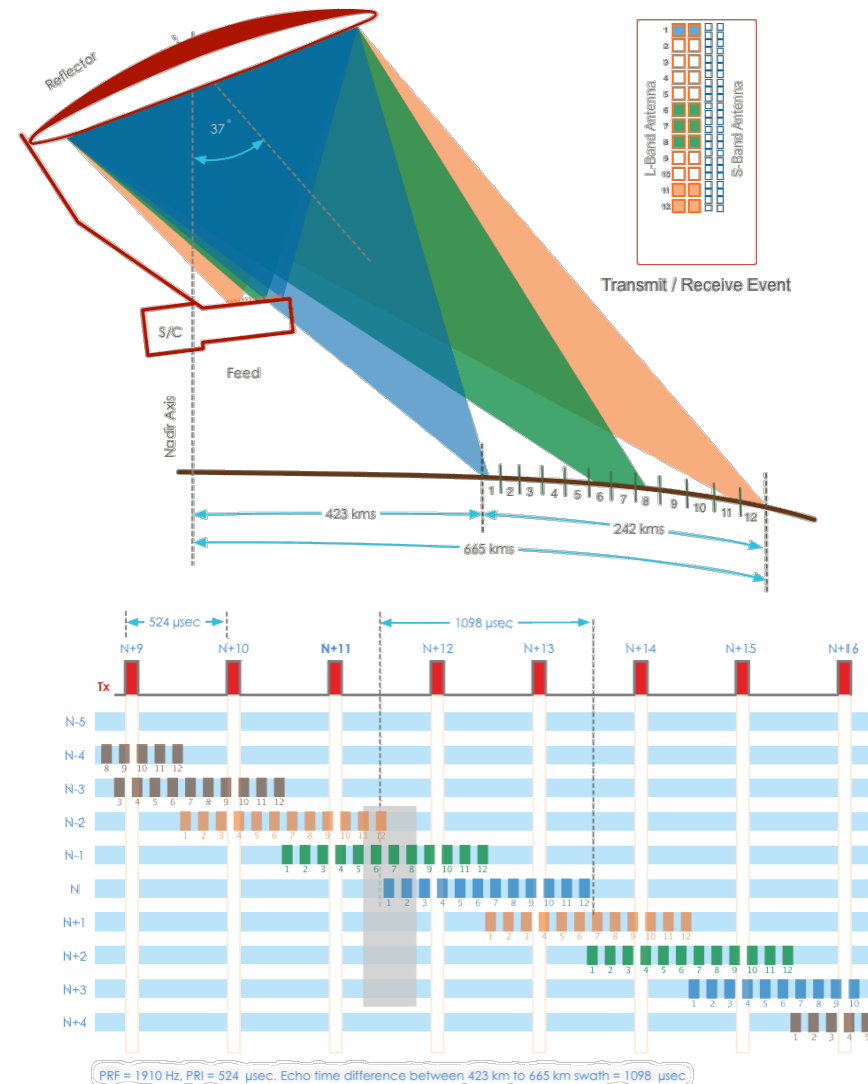
SweepSAR Measurement Technique

• SweepSAR Basics

- On Transmit, illuminate the entire swath of interest (red beam)
- On Receive, steer the beam in fast time to follow the angle of the echo coming back to maximize the SNR of the signal and reject range ambiguities
- Allows echo to span more than 1 Inter Pulse Period (IPP)

• Consequences

- 4 echoes can be simultaneously returning to the radar from 4 different angles in 4 different groups of antenna beams
- Each echo needs to be sampled, filtered, Beam-formed, further filtered, and compressed
- On-Board processing is not reversible – Requires on-board calibration before data is combined to achieve optimum performance



Toward Full Resolution and Wide Swath SAR

	Strip SAR	ScanSAR	TOPS	SweepSAR
Azimuth Resolution	Full (2-10 m)	Low (10-50 m)	Low (10-50 m)	Full (2-10 m)
Swath Width	Narrow (70-100 km)	Wide (200-400 km)	Wide (200-400 km)	Wide (200-400 km)
Radiometry	Uniform	Burst-Dependent	Uniform	Uniform
Interferometry	Uniform	Burst-Dependent	Burst-Dependent	Uniform
Polarization	Full	Full	Full	Full
Elevation Aperture Size	Nominal (0.5-3 m)	Nominal (0.5-3 m)	Nominal (0.5-3 m)	Narrow on transmit Wide on Receive (~1 m TX; ~10 m RX)
Aperture Scanning	None required	Electronic in Elevation	Electronic in Elev and Az	Electronic on Receive in Elevation

NISAR Mission Objectives Responsive to US National Academy

Key Scientific Objectives:

- Understand the response of ice sheets to climate change and the interaction of sea ice and climate
- Understand the dynamics of carbon storage and uptake in wooded, agricultural, wetland, and permafrost systems
- Determine the likelihood of earthquakes, volcanic eruptions, and landslides

Key Applications Objectives:

- Understand societal impacts of dynamics of groundwater, hydrocarbon, and sequestered CO₂ reservoirs
- Provide agricultural monitoring capability in support of food security objectives
- Apply NISAR's unique data set to explore the potentials for urgent response and hazard mitigation

To be accomplished in partnership with the Indian Space Research Organisation (ISRO) through the joint development and operation of a space-borne, dual-frequency, polarimetric, synthetic aperture radar (SAR) satellite mission with repeat-pass interferometry capability

ISRO Science and Applications Objectives



1. **Ecosystem Structure:** 1.1 Agriculture Biomass & Crop Monitoring; 1.2 Forest Biomass; 1.3 Biomass Change; 1.4 Mangroves / Wetlands; 1.5 Alpine Vegetation; #Vegetation Phenology and Vulnerability; #Vegetation soil moisture; #Ecosystem stress assessment.
2. **Land Surface Deformation:** 2.1 Inter-seismic / Co-seismic Deformations; 2.2 Landslides; 2.3 Land Subsidence; 2.4 Volcanic Deformations
3. **Cryosphere:** 3.1 Polar Ice Shelf / Ice sheet; 3.2 Sea Ice Dynamics; 3.3 Mountain Snow/ Glacier 3.4 Glacier Dynamics (Himalayan Region); #Glacier hazards; #Climate response to glaciers; #Advisory on safer marine navigation and sea ice.
4. **Coastal Studies & Oceanography:** 4.1 Coastal erosion / shoreline change; 4.2 Coastal subsidence and vulnerability to sea-level rise; 4.3 Coastal bathymetry; 4.4 Ocean surface wind; 4.5 Ocean wave spectra; 4.6 Ship detection; #Possible use of SAR for tropical cyclone; #Coastal watch services
5. **Disaster Response:** 5.1 Floods; 5.2 Forest Fire; 5.3 Oil Spill; 5.4 Earthquakes / Others
6. **Geological Applications:** 6.1 Structural & Lithological mapping; 6.2 Lineament mapping; 6.3 Paleo-Channel study; 6.4 Geomorphology; #Land degradation mapping; #Geo-archaeology; #Mineral explorations



NASA Requirements for NISAR

- From US Perspective, NISAR requires
 - Global coverage
 - Dense sampling in time
 - Vector measurements
- In order to accomplish new science
 - Global inventory of earthquakes and volcanos (above sea level)
 - Global inventory of biomass changes over the mission
 - Global inventory of wetlands and cultivated agriculture
 - Global dynamics of ice sheets and sea ice
- And to develop a community of applications users for
 - Disaster response
 - Infrastructure monitoring
 - Agriculture and forestry applications

NISAR

NASA-ISRO SAR Mission

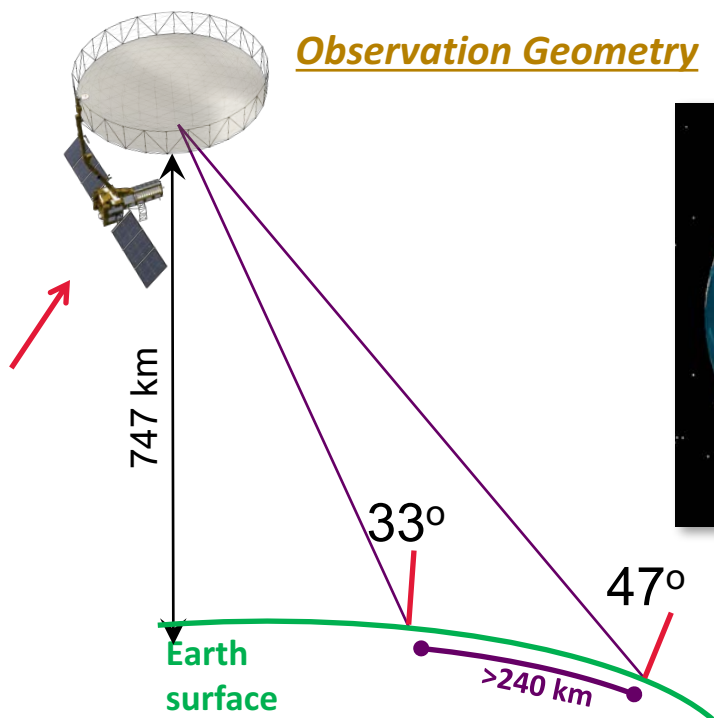
NISAR Characteristic:	Enables:
<i>L-band (24 cm wavelength)</i>	<i>Low temporal decorrelation and foliage penetration</i>
<i>S-band (12 cm wavelength)</i>	<i>Sensitivity to lighter vegetation</i>
<i>SweepSAR technique with Imaging Swath > 240 km</i>	<i>Global data collection</i>
<i>Polarimetry (Single/Dual/Quad)</i>	<i>Surface characterization and biomass estimation</i>
<i>12-day exact repeat</i>	<i>Rapid Sampling</i>
<i>3 – 10 meters mode-dependent SAR resolution</i>	<i>Small-scale observations</i>
<i>Pointing control < 273 arcseconds</i>	<i>Deformation interferometry</i>
<i>Orbit control < 500 meters</i>	<i>Deformation interferometry</i>
<i>L/S-band > 50/10% observation duty cycle</i>	<i>Complete land/ice coverage</i>
<i>Left/Right pointing capability</i>	<i>Polar coverage, north and south</i>



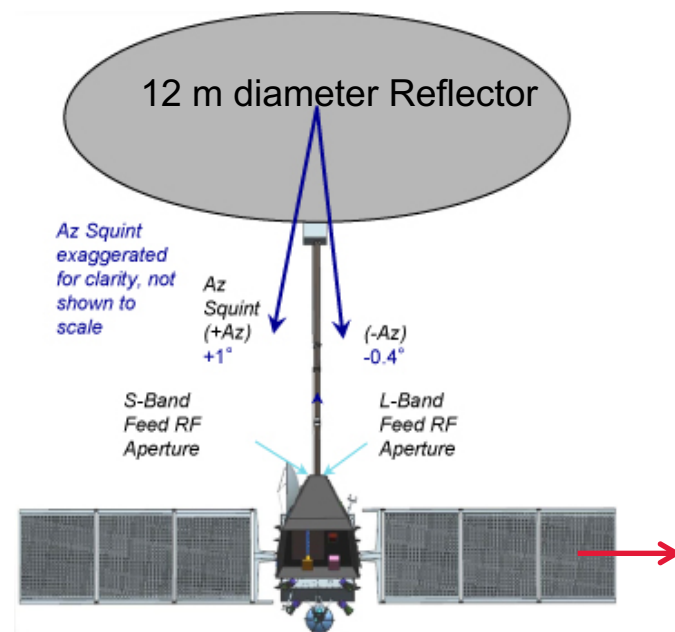
NISAR Imaging and Orbit Geometry

- Wide swath in all modes
- Data acquired ascending and descending
- Left/right pointing capability

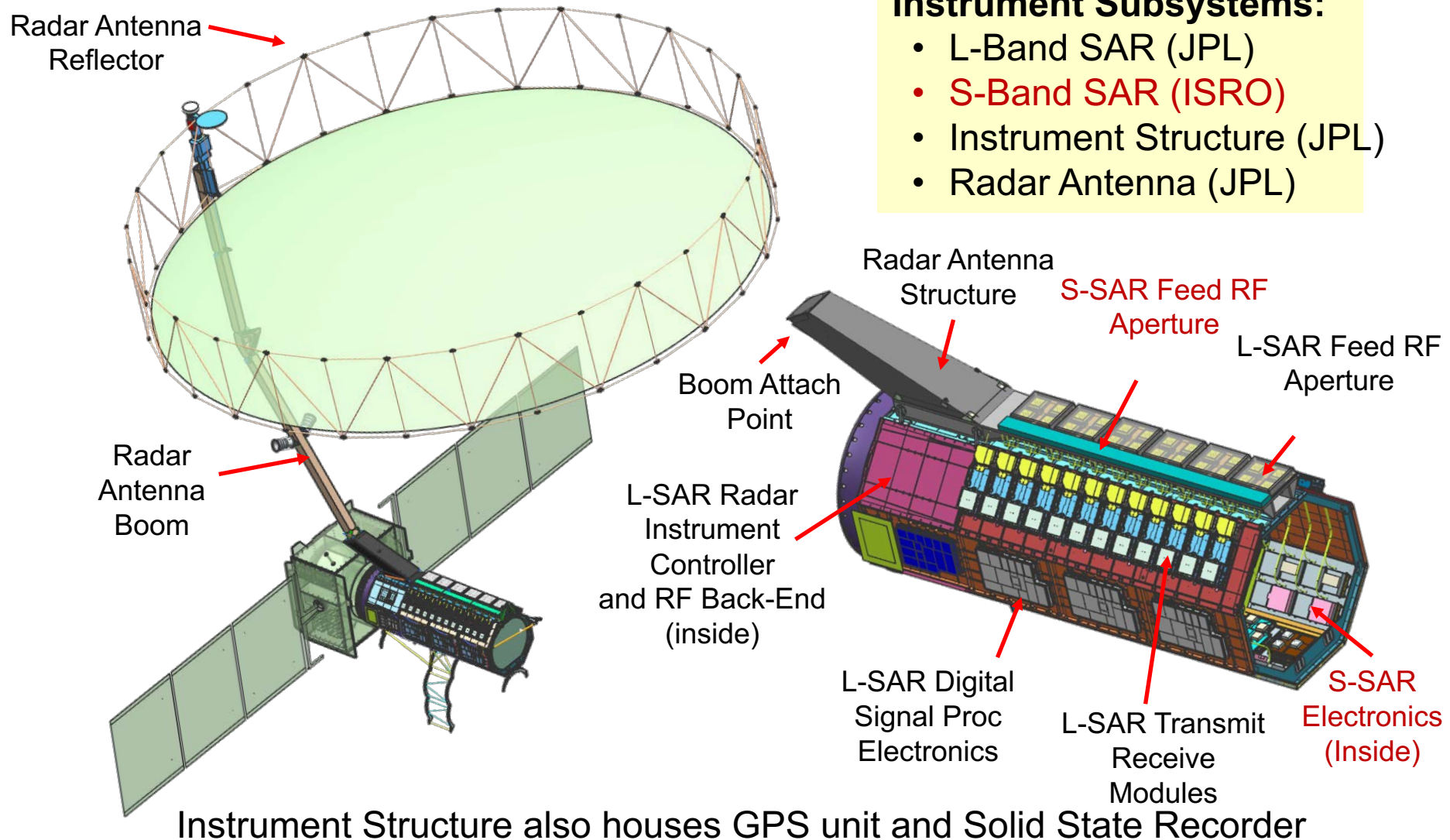
Observation Geometry



6 AM / 6 PM Orbit
98.5° inclination
Arctic Polar Hole: 87.5R/77.5L
Antarctic Polar Hole: 77.5R/87.5L

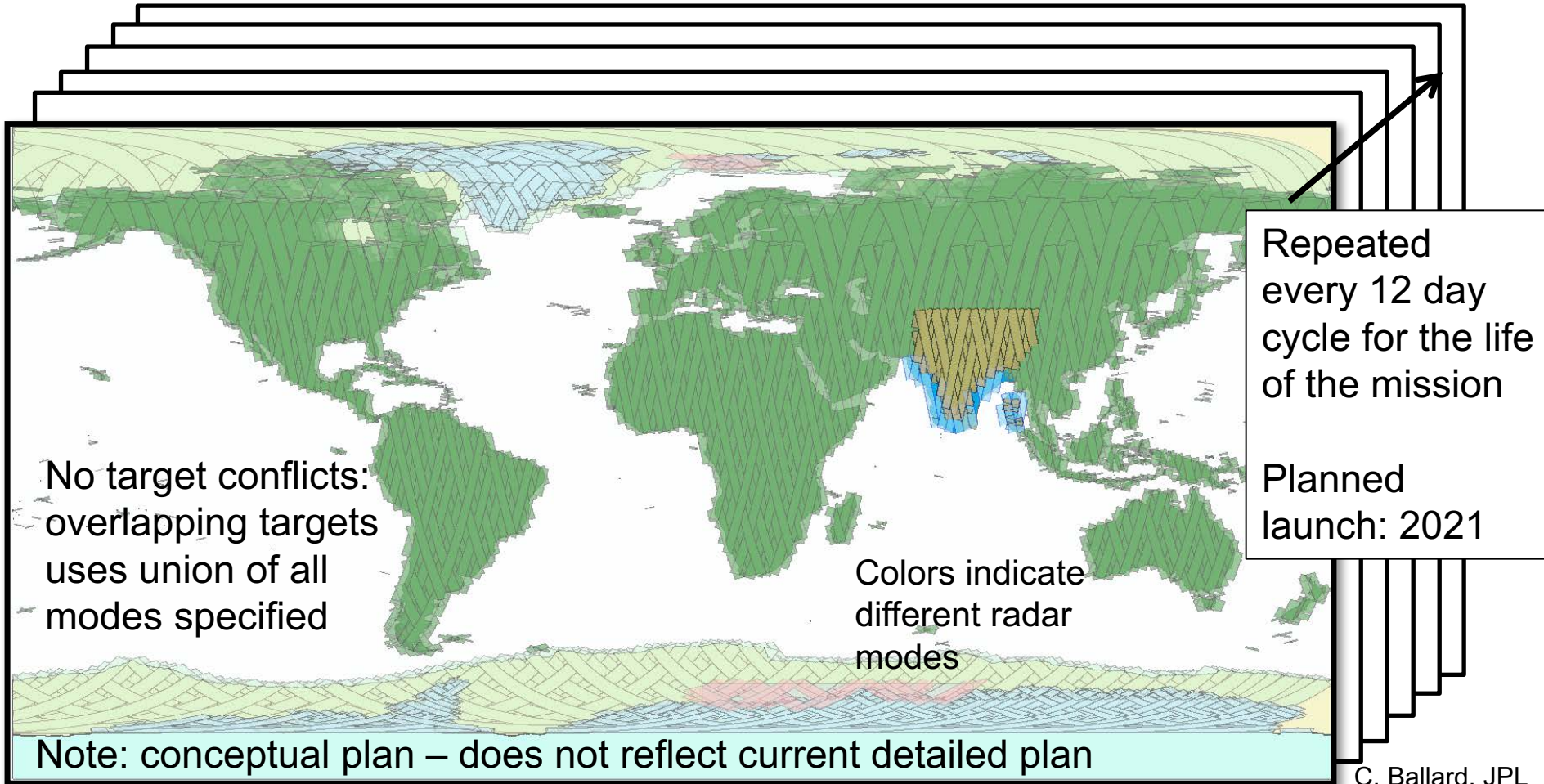


NISAR Instrument Overview



NISAR Systematic Observations

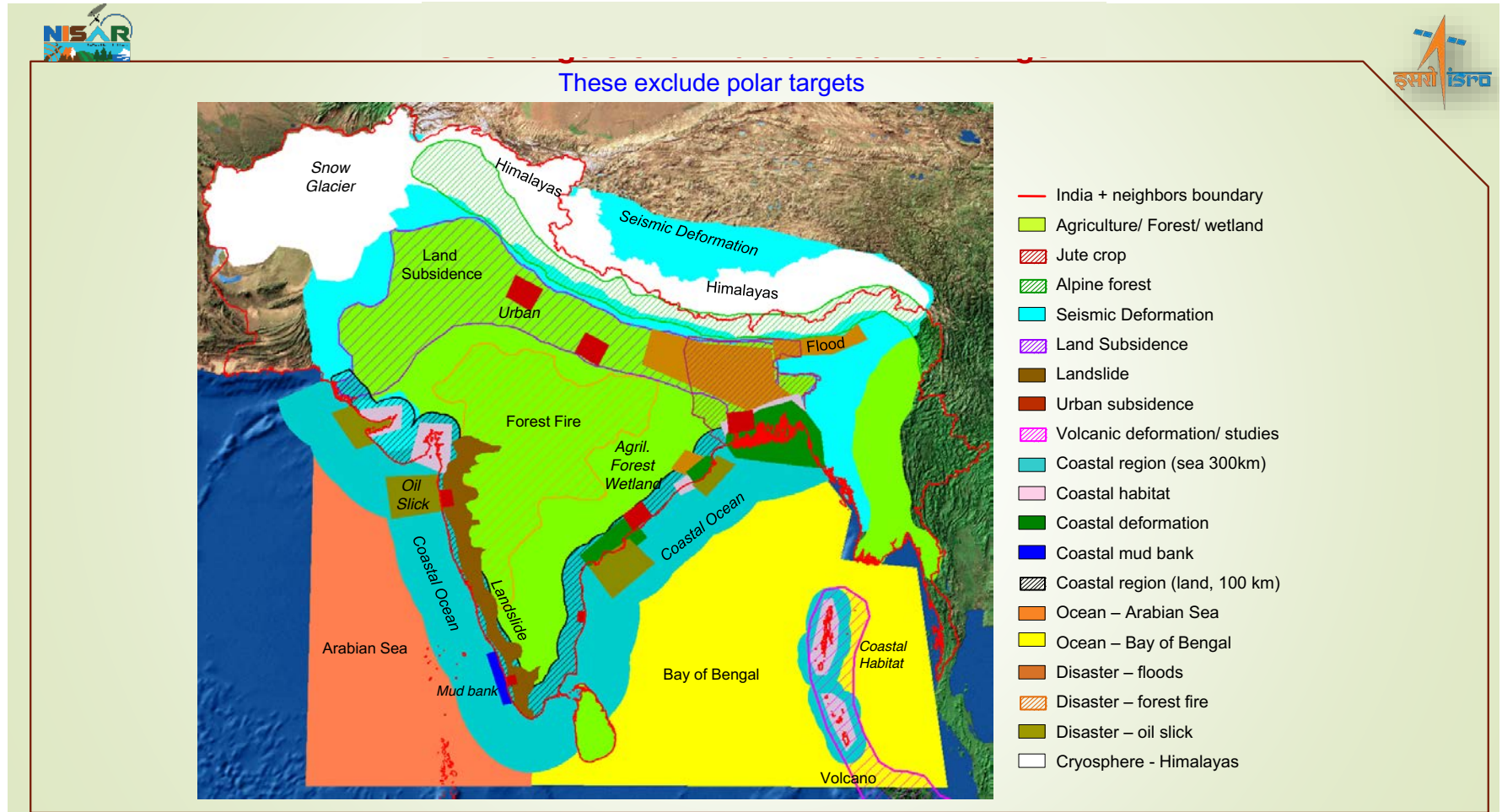
L-band globally – S-band regionally



C. Ballard, JPL

Persistent updated measurements of Earth – 50-100 PB of data



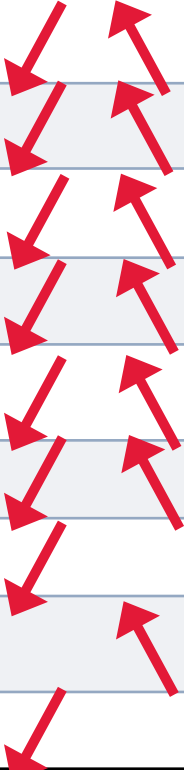






















ISRO Targets over India and Surroundings



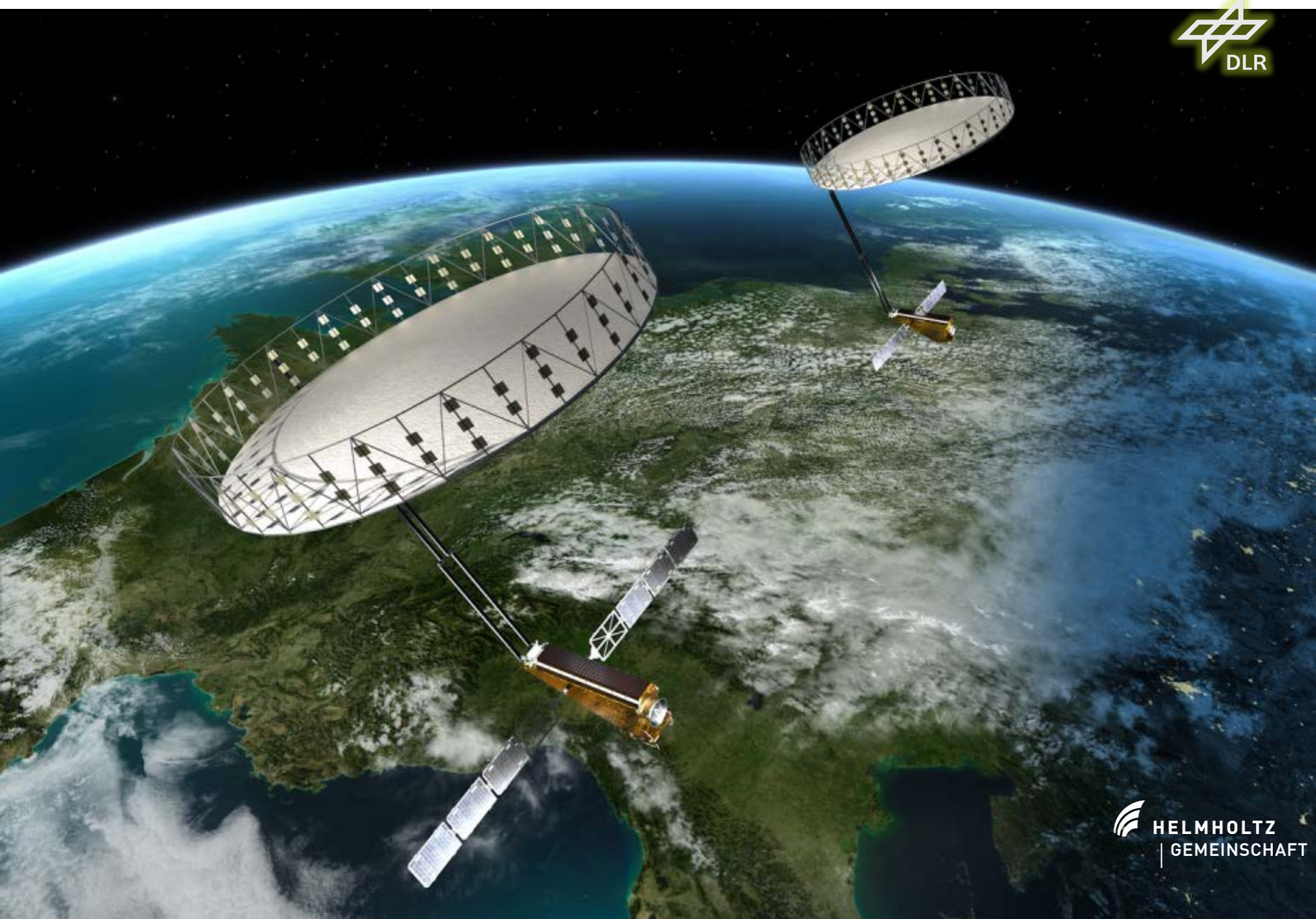
NISAR Science Observing/Operations Modes

Blanket Land and Ice Coverage Every 12 Days

- Observation strategy employs a subset of possible modes

Observation Strategy	L-band		S-band		Culling Approach	
Science Target	Mode ⁺	Resolution	Mode	Resol.	Sampling	Desc Asc
Background Land	DP HH/HV 	12 m x 8 m 			cull by lat	
Land Ice	SP HH 	3 m x 8 m 			cull by lat	
Sea Ice Dynamics	SP VV 	48 m x 8 m 			s = 1 p	
Urban Areas		6 m x 8 m 			s = 1 p	
US Agriculture	QP HH/HV VV/VH 				s = 1 p	
Himalayas			CP RH/RV 		s = 1 p	
India Agriculture					s = 1 p	
India Coastal Ocean			DP HH/HV or VV/VH 		s = 1 p	
Sea Ice Types	DP VV/VH 				s = 3 p	

Tandem-L



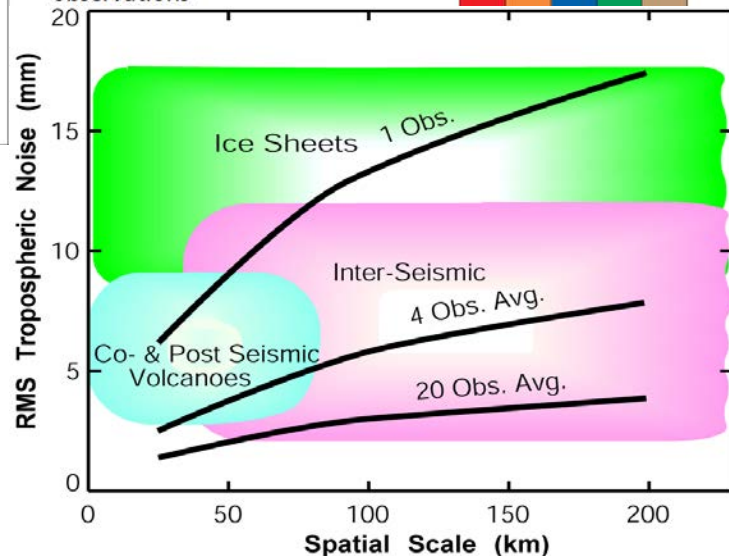
The Future: SAR for Science and Applications

Area	Benefit Through Regular SAR Monitoring of:
Global Food Security	<ul style="list-style-type: none">- Soil moisture and crop growth at agricultural scale- Desertification at regional scales
Freshwater Availability	<ul style="list-style-type: none">- Aquifer use/extent regionally- Water-body extent changes- Glaciers serving as water sources
Human Health	<ul style="list-style-type: none">- Moisture and vegetation as proxy for disease and infestation vectors
Disaster Prediction & Hazard Response	<ul style="list-style-type: none">- Regional building damage and change assessment after earthquakes- Earthen dams and levees prone to weakening- Volcanoes, floods, fires, landslides
Climate Risks and Adaptation	<ul style="list-style-type: none">- Ice sheet/sea-ice dynamics; response to climate change- Coastal erosion and shoreline migration
Urban Management and Planning	<ul style="list-style-type: none">- Urban growth through coherent change detection- Building deformation and urban subsidence
Human-activity Based Climate Change	<ul style="list-style-type: none">- Deforestation's influence on carbon flux- Oil and gas reservoirs

Recommendation from 2002 Solid Earth Science Working Group Report

Timeline Observational Strategies				Plate Boundaries	Land Surface Change	Ice and Ocean Dynamics	Magmatic Processes	Mantle Dynamics	Magnetic Field
	Immediate (1–5 Years)	Near Term (5–10 Years)	Long Term (10–25 Years)						
Surface deformation	<p>Single dedicated InSAR satellite</p> <ul style="list-style-type: none"> L-band, left/right looking capability, and weekly access to anywhere on the globe Precise orbit determination and ionospheric correction capabilities 1 mm/yr surface displacement over 50-km horizontal extents in selected areas 	<p>Constellation of InSAR satellites</p> <ul style="list-style-type: none"> Improved temporal frequency of deformation maps to daily intervals Maps at several-hundred-km width with full vector surface displacements at accuracies of submillimeter per year over 10-km spatial extents and 1-m spatial resolution Complementary ground and seafloor geodetic observations 	<p>Constellation of InSAR satellites in low-Earth or geosynchronous orbits</p> <ul style="list-style-type: none"> Hourly global access Increased density of continuous ground and seafloor geodetic observations 						

- Community has bold vision for continuous monitoring of Earth's solid earth processes
- Requires dense spatial and temporal sampling



What about a constellation of satellites to achieve same capabilities?

Constellations of smaller, standardized satellites are being developed to lower cost and develop commercial markets

Capability	NISAR	Small SAR
Wavelength	L and S-band	X through L various
Repeat Pass Interferometry – orbit and pointing control	< 0.1° pointing stability < 300 m orbit tube	?
12-day sampling – wide swath	240 km strip	~30 km strip
Polarimetry – aperture size and power, data rate and volume	SP-QP: 12 m diameter aperture	SP-QP: ~5-10 sqm
Resolution – data rate and volume	3-10 m res ~ 1 Gbps	3-10 m res ?
Persistent Global coverage – on-orbit duty cycle	> 50%	~10%

Number of small SAR satellites to achieve NISAR

NISAR Swath NISAR L-band duty cycle NISAR S-band duty cycle

$$N_L = \frac{240 \times 0.5}{S \times T_o}$$

smallSAR Swath Small SAR duty cycle

$$N_S = \frac{240 \times 0.1}{S \times T_o}$$

- Under assumptions on previous page
 - 40 L-band radar satellites
 - 8 S-band radar satellites

What about continuity beyond NISAR? Or Densification?

- NISAR represents the first step toward SESWG and continuing community recommendations
 - 1-day repeat
 - Global coverage
 - Finer resolution
 - Greater vector diversity
 - Multi-decade time series
- Means for continuity in the age of affordability
 - International coordination
 - SmallSAT constellations (Public and private)
 - Rethink science requirements

Low Cost Constellation of Radar Satellites?

- Needs disruptive cost reduction of systems requiring large power x aperture product

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Summary

- Synthetic Aperture Radar has evolved from an “imager of last resort” to a go-to methodology for science and applications
- The demand for faster sampling in time and finer resolution has driven many innovations in SAR technology and techniques
- In addition to “flagship missions” from international space agencies, opportunities exist to innovate:
 - low cost electronics and apertures
 - Distributed autonomous systems
 - Intelligent observing systems that deliver science ready data from space



Jet Propulsion Laboratory
California Institute of Technology